A GEOCHRONOLOGICAL STUDY OF THE LONE GROVE PLUTON FROM THE LLANO UPLIFT, TEXAS

Thesis by
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ABSTRACT

A detailed geological study of the Lone Grove granitic pluton and surrounding rocks from the Llano Uplift, Texas, was made. Field and petrologic evidence suggests that this intrusive has had a simple history of emplacement with no later metamorphism. Samples of granite, aplite, pegmatite, rhyolite, and metamorphic rocks were investigated geochronologically in order to determine the consistency in Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages between various minerals and between different localities. Refined chemical and mass spectrometric methods of analysis are described and the limits of precision are established. It is found possible to determine ages on most highly radiogenic minerals to a precision of $\pm 1\frac{1}{2}\%$ or better. All ages were calculated with the following decay constants: Rb^{87}, $\lambda_\beta = 1.47 \times 10^{-11}$ yr^{-1}; K^{40}, $\lambda_\beta = 4.72 \times 10^{-10}$ yr^{-1} and $\lambda_e = 0.585 \times 10^{-10}$ yr^{-1}. The distribution of ages on most of the minerals from these rocks show a spread commensurate with the experimental error. The average Rb^{87}-Sr^{87} age on microclines, muscovites, and biotites is 1015 million years and the average K^{40}-Ar^{40} age on muscovites, biotites, and hornblendes is 1045 million years. A total rock Rb^{87}-Sr^{87} age on one of the granites gives no indication of having an older age than the constituent minerals. The only rock to show an apparently real different age is a rhyolite porphyry, which gives an average Rb^{87}-Sr^{87} microcline age of 910 million years. K^{40}-Ar^{40} determinations on several microclines and

plagioclases give ages which are 5-20% too low, presumably due to argon diffusion from the feldspar. Anomalously low Rb^{87}-Sr^{87} ages occur on several biotites from fresh pegmatites and granite. Evidence is presented for radiogenic strontium migration from these rocks although the exact nature of the process is not known. Somewhat low K^{40}-Ar^{40} ages also are obtained on the pegmatitic biotites. A study of the effects of weathering on the geochronologic systems is made on two obviously altered granites. The only mineral to suffer any decrease in age from such surface alteration is biotite by the Rb^{87}-Sr^{87} method. The isotopic composition of the common strontium incorporated into the minerals of the granite is determined on several minerals having low Rb/Sr ratios. The Sr^{87}/Sr^{88} ratio is found to be 0.0843 ± 0.0002 (normalized to make $Sr^{86}/Sr^{88} = 0.1194$). A discussion of the distribution of rubidium, potassium, and normal strontium throughout the pluton is given and several partitioning factors for the rubidium to potassium concentrations between different mineral species are calculated.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

INTRODUCTION

A detailed field and laboratory study of a granitic pluton was undertaken with the purpose of gaining some understanding of the occurrence and behavior of those elements involved in potassium-argon and rubidium-strontium geochronology. The distribution of these elements between the various mineral phases, the ability of the minerals to remain closed systems after initial crystallization, and a comparison of mineral ages between different localities within an intrusive are important aspects of this problem. Before one proceeds into the study and interpretation of a more complicated multi-event terrane, it would be extremely profitable to investigate what we might call the zeroth order case in which all geochronologic clocks were set at one time and have remained undisturbed ever since. The behavior of the various mineral systems under such ideal conditions would allow us to establish certain limits on the inherent ability of these systems to provide geochronological and related chemical information. It was therefore desirable to select an intrusive which had rather straightforward structural relationships and a simple geologic history. The Pre-Cambrian granitic batholiths exposed in the Llano Uplift of central Texas appeared to be suitable for this study. A considerable amount of literature is available on the structure, petrology, and chemistry of this area. There are also several absolute age determinations available from earlier workers which suggest a concordant age for these rocks. The granites are of sufficient age and appropriate composition to

contain favorable parent-daughter ratios for several minerals; they show no signs of having suffered subsequent metamorphism after emplacement; and they appear to be structurally and petrologically uncomplicated.

A roughly circular pluton approximately twelve miles in diameter, which has been called the Lone Grove body by Stenzel (1936) and renamed the Buchanan massif by Keppel (1940), was chosen for detailed study because of its excellent quarry and road-cut exposures, its documentation in the literature, and its simple geometric structure. It is located in Llano and Burnet counties near the northeastern edge of the Pre-Cambrian exposure. An area of approximately 275 sq.mi. which includes this pluton and the surrounding terrane has been mapped on a scale of 1" = 1 mile (Fig. 1, Plate I), and a detailed petrological study of the rock was made. Suites of minerals from several sample localities from the granite and related pegmatites and aplites have been analyzed by refined chemical and mass spectrometric methods in order to determine the consistency in radiogenic ages between various minerals and between different localities within an individual pluton. Rubidium^{87}-strontium^{87} ages were determined on microclines, biotites, and muscovites, and potassium^{40}-argon^{40} ages were determined on microclines, plagioclases, biotites, muscovites, and hornblendes. Total rock Rb^{87}-Sr^{87} analyses were also made on several of the samples. The strontium isotopic composition was measured on several minerals having a low Rb/Sr

ratio, and the initial isotopic composition at the time of crystallization was calculated. Ages were also obtained on several other intrusive bodies and the country rock from the Uplift in order to see if any significantly older or younger event was discernible.

PREVIOUS INVESTIGATIONS

The earliest recognition of Pre-Cambrian rocks in central Texas was by T. B. Comstock (1890), who first applied the terms Packsaddle schist and Valley Spring gneiss to the metamorphic rocks of the area. Sidney Paige (1911, 1912) made a geologic map of the Llano-Burnet quadrangles and redefined the major metamorphic and igneous units. H. B. Stenzel (1932, 1934, 1936) further studied the granites of the Llano Uplift and made a structural map of one of the plutons. He was able to divide the granites of the area into three textural varieties--the Sixmile granites, the Oatman granites, and the Town Mountain granites. David Keppel (1940) also made a structural investigation of the intrusive rocks and mapped in some detail the area including the Lone Grove pluton. A chemical and petrologic examination of several granites, including those of the Lone Grove pluton, was conducted by Goldich (1941), who also made a weathering study of the rocks (1938).

Several mineralogical investigations have been made on the rare-earth deposits of the region, which include the Baringer Hill pegmatite within the Lone Grove pluton. Hess (1908) and Landes (1932) gave descriptions of the material obtained from this pegmatite, and Barrell (1917) and Holmes (1931) gave some chemical lead ages on several of the radioactive minerals.

Numerous detailed publications have been made on the petrology, structure, and economic value of the rocks of the Llano Uplift within the past two decades. Some of the major contributors

to the geology of the Llano Uplift include Barnes, Dawson, and Parkinson (1947), Hutchinson (1956), and Flawn (1956).

Hutchinson, Jaffe, and Gottfried (1954), Hutchinson (1956), and Flawn (1956) gave several zircon lead-alpha ages for the granites of the region, which generally range between 800 and 900 million years and are 10-20% lower than isotopic analyses. Hurley and Goodman (1943) obtained a helium age of 1050 million years on magnetite from Llano County.

More recent geochronologic work on the Pre-Cambrian rocks of central Texas have included several Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages by Aldrich, Wetherill, Davis, and Tilton (1958), Goldich, Nier, Baadsgaard, Hoffman, and Krueger (1961), and Wasserburg, Wetherill, Silver, and Flawn (1962). Aldrich, Wetherill, Davis, and Tilton (1958) also have determined the U-Pb and Th-Pb isotopic ages on a zircon from one of the granites. All of these measurements have suggested a rather uniform age of 1000-1100 million years for these rocks.

GEOLOGY

Regional

The exposed Pre-Cambrian basement of the Llano Uplift provides us with a window into the rocks of the Texas Craton. This structural province, which has been defined both from surface and subsurface studies by Flawn (1956), is an area characterized by metasedimentary rocks which have been thoroughly invaded by intrusive rocks, especially of granitic and granodioritic composition. Radiogenic ages from both surface and well core samples in central and western Texas suggest an age of 1000-1100 million years for the rocks of this craton (Aldrich, Wetherill, Davis, and Tilton, 1958; Goldich, Nier, Baadsgaard, Hoffman, and Krueger, 1960; Wasserburg, Wetherill, Silver, and Flawn, 1962).

Paige (1912) made the first detailed geologic study of a part of the Llano Uplift in the U. S. Geological Survey Folio of the Llano-Burnet quadrangles. He divided the Pre-Cambrian metamorphic rocks of the area into two formations. These included an older quartz-microcline-biotite gneiss, the Valley Spring gneiss, and an overlying sequence of micaceous schists, graphitic schists, amphibolites, marbles, and calc-silicate rocks, the Packsaddle formation. Although more recent studies have cast some doubt on this simple classification and have suggested that each of these formations may represent more than one sequence of metamorphic rocks, the terminology of Paige still predominates in the literature and will be used in this paper. No complete section of either unit

has been measured, but it is likely that they are measurable in thousands of feet.

The Valley Spring gneiss is a predominantly fine-grained, well foliated to massive, pinkish gneiss with local pinkish-gray biotitic bands. Some rather pure quartzitic beds are also included in the gneiss. The rock appears to have originated as an arkosic sandstone with minor orthoquartzitic beds. A few wollastonite bands have been encountered within the gneiss, but calc-silicate rocks are far more abundant in the Packsaddle formation. Locally, as in east-central Mason County, bands of magnetite lie within the Valley Spring gneiss. It is possible that some of the Valley Spring gneiss was originally an acidic igneous rock, either intrusive granite or extrusive rhyolite. Wherever the Valley Spring gneiss becomes intimately involved with later igneous activity, it becomes partially recrystallized and often highly contorted. Regionally, it has been noted that this rock, as well as the overlying Packsaddle formation, appears to increase in degree of metamorphism from northwest to southeast. This increase in metamorphism correlates with increased igneous activity of basic and ultrabasic rocks, which are concentrated in the southeastern portion of the Uplift.

The Packsaddle formation consists of a dark-colored series of metamorphic rocks, which include mica, amphibole, and graphite schists and crystalline limestones. The rocks are generally well foliated parallel to lithologic layerings. This sequence of rocks probably originated as sandstones, graywackes,

shales, and limestones deposited in a shelf-type marine environment. The more basic amphibolites may have been volcanic flows or sills. Like the Valley Spring gneiss, the Packsaddle formation is highly deformed and altered near contacts with later intrusive rocks. Inclusions of schist, calc-silicate rock, and soapstone from the Packsaddle formation in these later intrusives are quite common. Also, similar to the Valley Spring formation, the Packsaddle formation shows an increase in metamorphic grade from northwest to southeast. Although it is impossible to follow specific units across this metamorphic gradient, the appearance of higher and higher grade minerals within the Packsaddle formation toward the southeast is quite noticeable. Chlorite schists found chiefly in the northwestern portion of the area give way to biotite and muscovite schists throughout the central portion of the area, and garnet-bearing schists appear to be present only in the southeastern part of the Uplift. Although still higher grade mineral assemblages occur locally within the area, they are usually directly attributable to contact metamorphism associated with an adjacent pluton.

Structurally, the metamorphic rocks of the Llano Uplift are folded into broad northwest-southeast trending synclines and anticlines. These rather open major folds, which are commonly traceable along the entire length of the basement outcrop, are in turn highly crenulated and folded by numerous smaller scale structures. Generally, Valley Spring gneiss is exposed along the axes of the anticlinoria and Packsaddle formation is preserved in the troughs of the synclinoria. The structure appears locally to affect

the emplacement of granitic plutons. Several phacoliths appear to intrude along axes of plunging synclines near the Valley Spring-Packsaddle contact.

Intrusive metaigneous and igneous rocks varying in composition from ultramafic serpentinites through basic and intermediate rock types to granites and accompanying acidic dikes and pegmatites are found within the Pre-Cambrian complex. Of these rock types, only the younger granitic batholiths, stocks, and dikes occur abundantly throughout the Llano Uplift. Most of the older and more basic intrusive rocks are concentrated in the southeastern portion of the exposed basement complex. Here occur, in addition to the ubiquitous granites, serpentinite, hornblendite, diorite, gabbro, quartz diorite gneiss, and granite gneiss. Although the exact interrelationships of these igneous rocks are not clear, structural evidence shows that they most certainly predate the granite batholiths. Since they do not occur in the immediate vicinity of the sample localities included in this study and have had no effect upon the post-granite history of the area, no further description of them will be presented.

By far the most abundant igneous rock types present within the Llano Uplift are granites and granodiorites. Stenzel (1934) has been able to identify three separate types of granitic rocks from the region; they are in order of postulated increasing age (1) the Sixmile granites; fine- to medium-grained, gray biotite granites; (2) the Oatman granites; medium-grained, gray to pink, cataclastic granites; and (3) the Town Mountain granites; coarse-

grained to porphyritic granites, commonly with large flesh-colored feldspars. Further work has cast some doubt on the occurrence of three distinct granite types. Rocks showing almost complete gradation in texture and composition between the three types have been found, and it is possible that all of the granites were evolved by the fractionation of one or more related or chemically analogous liquids. The granites occur in varying shapes and sizes ranging from small dikes and veinlets to large stocks and batholiths covering over 100 sq. mi. Structurally, there is evidence that some of the larger plutons tend to occur as phacoliths which are localized near the Valley Spring-Packsaddle contact, while others appear to be cylindrical in shape and extend to considerable depth.

The Town Mountain granite, which makes up the bulk of the larger granitic intrusives, is composed of quartz, microcline, plagioclase (oligoclase to andesine), and biotite. Hornblende is also commonly present and in some localities it makes up more than 5% of the rock. Secondary albite is always present as exsolution lamellae in the microcline and as distinct grains throughout the rock. Accessory minerals include zircon, allanite, magnetite, apatite, fluorite, and sphene. Chemical analyses of the rock show it to be rather uniform in composition and ranging from granitic to granodioritic in type. The Sixmile and Oatman granites differ somewhat in chemical composition and mineralogy from the Town Mountain granite; however, the chief difference between these rock types appears to be a textural one.

There is presently no strong evidence indicating a source for these granitic intrusives. The question as to whether they were produced by a partial fusion and differentiation of some lower crustal or subcrustal material, or whether they represent the melting of a more shallow rock type such as the Valley Spring gneiss is open to conjecture. Detailed structural studies of these granites have generally led to the conclusion that they are truly magmatic in origin and have come into their present position in at least a partially molten state.

Many pegmatite and aplite dikes which are related to the granites are found cross-cutting both the granites themselves and the surrounding wall rocks. Quartz veins are also abundantly distributed within the plutons and adjacent country rock. The pegmatites range in size from a few inches to hundreds of feet in length and are chiefly composed of microcline and quartz with or without biotite and muscovite. Accessory minerals range from quite rare to rather abundant. Fluorite, tourmaline, garnet, gadolinite, molybdenite, cassiterite, topaz, and native bithmuth are among the minerals which have been found in some of the pegmatites. The aplites are typically fine-grained, gray to pink, and sugary in texture. They are composed of equigranular grains of quartz, albite, and microcline with accessory biotite and fluorite. These aplite dikes commonly grade into pegmatite in their cores; this phenomenon is especially prevalent in the plutons of the Town Mountain granite. A dike system of granite porphyry (llanite), containing phenocrysts of pink microcline and blue,

opaline quartz, occurs in northern Llano County and appears to postdate the granite emplacement. The time interval between the granite and porphyry intrusions cannot be determined from field relationships. The limited size and extent of this dike system suggests that it would not have a pervasive effect upon the area.

Sharply contrasting with the metamorphic and igneous basement complex of the Llano Uplift are the overlying sedimentary rocks of Paleozoic and Mesozoic ages. Although we have little evidence of what transpired between the final period of Pre-Cambrian igneous activity and the onset of Paleozoic sedimentation, it is evident that a substantial quantity of basement rock was removed by erosion during this time in order to bring these plutons to the surface. The sedimentary rocks include the Upper Cambrian Riley and Wilberns formations, the Lower Ordovician Ellenburger group, and overlying Devonian, Mississippian, Pennsylvanian, and Cretaceous strata. A detailed description of these flat-lying to slightly dipping sedimentary rocks is beyond the scope of this paper. Suffice it to say that a study of these units is helpful in deciphering the history of the Llano Uplift during Phanerozoic time. In general, these rocks show strong evidence for repeated cycles of uplift and submergence of the area during this time. Wide variations in the thicknesses and lithologies of most of these units attest to local variations in their depositional environment and subsequent exposure to erosion. Locally Cretaceous rocks rest directly upon the Pre-Cambrian basement and indicate either the complete removal or non-deposition of the Paleozoic sequence in

that area. A maximum thickness of approximately 5000' of Paleozoic and Cretaceous sediments has overlain the Uplift at some time during its history. Although late Paleozoic normal faulting possibly related to the Ouachita orogeny has disrupted the Paleozoic and older basement rocks of the area, no evidence of severe deformation or metamorphism subsequent to Upper Cambrian time is recorded in these sedimentary rocks.

Lone Grove Pluton

A detailed field and petrological investigation of one of the granitic plutons was made in conjunction with the geochronologic study. It was thereby hoped that correlations, if any, which might exist between the structure, mineralogy, and texture of the granite and the resulting geochronological data would be revealed. Plate I is a geological map of the Lone Grove pluton, the intrusive which was chosen for this study. The map area includes parts of Llano and Burnet counties in the Central Texas hill country. The relief of the land underlain by the granite is generally less than 100', while the surrounding Pre-Cambrian schists and gneisses and Paleozoic sediments commonly form hills and escarpments with a relief in excess of 500'. Two artificial lakes which impound the water of the Colorado River lie within the map area. Lake Buchanan covers approximately the eastern quarter of the Lone Grove pluton while Inks Lake lies mainly within the Valley Spring gneiss. Texas highway 29, which traverses the area in an east-west direction, and numerous paved and gravel secondary roads provide ready access to most of the region. The communities of Buchanan Dam,

Tow, Bluffton, and Lone Grove and several new resort developments along Lake Buchanan and Inks Lake constitute the major population concentrations in the area. Most of the remaining country consists of ranch and farm land.

The mapping was carried out during the falls of 1960 and 1961. A reconnaissance study was made of approximately 275 sq. mi. which included the Lone Grove pluton and surrounding geology. The Paleozoic structure has been modified after the work of Paige (1912), and certain contacts now covered by Lake Buchanan were taken from Keppel (1940).

The Lone Grove pluton is a roughly circular, steep walled granitic intrusive approximately 12 miles in diameter. It is composed predominantly of the typical Town Mountain type granite of Stenzel (1934). Previously, Keppel (1940) has made a structural investigation of this "massif" and was able to identify several textural varieties of granite which occur as concentric bands in the pluton. He concluded that the sequence of solidification, proceeding from the wall inward, includes a coarse-grained granite, a porphyritic coarse-grained granite, and a medium-grained granite. Late stage small bodies and dikes of fine-grained granite cut these earlier members of the pluton and also invade the surrounding country rock. Stenzel (1936), Barnes, Dawson, and Parkinson (1947), and Hutchinson (1956) have made detailed studies of some of the other major batholiths in the Llano Uplift. Many of the structural, petrological, and chemical features found by these workers are characteristic of all the plutons in the area. The

interested reader is referred to these earlier investigations, which include descriptions of the structure, petrofabrics, chemistry, and paragenesis of the granite.

A second major granite intrusive lies partially within the southern part of the map area and is separated from the Lone Grove pluton by a thin septum of Packsaddle schist. This body, called the Kingsland massif by Keppel (1940), is mineralogically similar to the Lone Grove massif, but it is texturally somewhat different, being in general finer grained and more porphyritic. In addition, several smaller bodies of granite and aplogranite intrude the metamorphic terrane within the map area. A part of the granite porphyry (llanite) dike system occurs in the northwest portion of the area.

Highly deformed Valley Spring gneiss and Packsaddle formation form the country rock into which these igneous rocks were intruded. Horizontal, unmetamorphosed Paleozoic sediments overlap the basement complex in the northern and eastern portions of the map area and occur elsewhere as isolated remnants.

The rocks within the Lone Grove pluton range from pinkish-gray, coarse-grained, seriate to non-seriate porphyritic granite through reddish-pink medium-grained granite to deep red, fine-grained granite and aplogranite. The coarse- and medium-grained varieties are distributed in a concentric pattern within the pluton, with the coarse-grained granite forming the periphery and the medium-grained granite the core. Fine-grained granite and aplogranite occur as intrusive stocks and dikes in the other members

of the pluton and adjacent wall rock. Detailed petrographic descriptions and modal analyses of individual samples from the pluton employed in this study are given in the Appendix.

Coarse-grained granite:

The coarse-grained granite, or more properly adamellite, consists of perthitic microcline, quartz, plagioclase, biotite, and hornblende. Accessory minerals include apatite, allanite, zircon, sphene, fluorite, and magnetite (ilmenite). The microcline commonly contains from 10 to 30% exsolution albite, which occurs as patches and lamellae throughout the grain. Rapikivi and antirapikivi textures are frequently developed between the microcline and plagioclase, especially in the phenocrysts of the more porphyritic varieties. The primary plagioclase is oligoclase in composition and generally shows well-developed albite twinning. The quartz forms anhedral, clear to slightly bubbly, unstrained grains in the groundmass. Biotite and hornblende, commonly in aggregates and clusters containing poikilitic intergrowths of each other, are the chief mafic constituents of the rock.

The coarse-grained granite varies both in texture and composition between the outer margin and the core boundary. In general, the rock becomes coarser grained and more distinctly porphyritic toward the core. Whereas the granite near the margin of the pluton tends to have a seriate grain size distribution, it becomes increasingly more bimodal inwardly. In the granite near the margin the feldspar grains show a complete range in size between those of the groundmass and the larger phenocrysts; however,

they become increasingly more non-seriate toward the core until a definite hiatal texture is developed. It is these extreme textural varieties which Keppel (1940) has arbitrarily divided into coarse-grained and coarse-grained porphyritic granite. The average grain size of the groundmass ranges from 5 to 10 mm, while the feldspar phenocrysts attain a maximum length of about 25-30 mm at the margin and over 60 mm near the core. A slight increase in perthitic microcline and a corresponding decrease in quartz and plagioclase appear to be the major compositional trends accompanying this increased porphyritic development. An increase in the percent of secondary exsolved albite in the microcline and a decrease in the hornblende to biotite ratio also appear to take place as one proceeds from the margin to the core of the pluton.

The maximum length of the largest feldspar phenocrysts has been measured at approximately 40 stations within the coarse-grained granite of the Lone Grove pluton, and a similar set of measurements was also taken on the Kingsland pluton. These data were then used to construct the contours shown on Plate I. Between 25 and 50 of the largest feldspar phenocrysts at a given station were measured in order to determine their greatest length. A fairly well defined maximum size could be established in this manner which was generally reproducible to ±4 mm. At a given station phenocrysts which are considerably larger than any others are extremely rare, and, where encountered, they have not been included in the data. Although the details of the contour pattern may be somewhat in error, it certainly shows the general nature of the variations in phenocryst size. As stated above, the

phenocrysts in the coarse-grained granite of the Lone Grove pluton tend to increase radially toward the core. In contrast, the phenocryst size in the Kingsland pluton appears to show a pattern totally unrelated to the shape of the intrusive. Instead, a series of elongate maxima and minima cross the pluton in a west-northwest to south-southeast direction and abut directly against the margin of the intrusive. Since the trend of these zones is roughly parallel to the regional folding of the metamorphic rocks, it may reflect some structural control in the intrusion of the granite. Nevertheless, it is difficult to explain these radically different patterns in two immediately adjacent plutons.

The most obvious petrofabric features of the granite are planar flow structures, linear flow structures, and joint systems. A well developed vertical to steeply dipping flow foliation which generally parallels the adjacent border of the pluton is produced by an alignment of platy biotite and microcline grains, layering of biotite-rich schlieren, and the orientation of pod-shaped xenoliths of metamorphic rocks. A much more poorly developed flow lineation lying in the plane of the foliation and generally plunging almost vertically is formed by elongate, spindle-like grains and aggregates of microcline, quartz, and biotite. Although both the flow foliation and lineation are best developed near the border of the pluton, these structures persist throughout the entire coarse-grained granite. a-b and a-c joints as well as several sets of unidentified joints which may be related to a regional stress pattern were encountered in the field; however, the joint structure has not been

mapped in this investigation.

A border facies of foliated, gray, coarse-grained, porphyritic granite lies along the western edge of the pluton. This rock, which extends from just north of the Llano River to approximately $\frac{1}{2}$ mile north of Lone Grove, differs both in texture and composition from the typical coarse-grained granite. It contains over 7% biotite as the only mafic mineral, and locally shows pyrite mineralization. The vertical foliation of this rock is produced by the strong mineral alignment of microcline phenocrysts and biotite parallel to the adjacent wall rock. Although a prominent fault zone lies immediately to the west of this granite, only minor evidence of shearing and cataclastic disruption of the rock is evident. Keppel (1940) found a similar foliated granite near the eastern margin of the pluton; however, that locality is now covered by Lake Buchanan.

The granite of the Kingsland pluton has not been investigated in detail. A reconnaissance study shows it to be chemically and mineralogically quite similar to the coarse-grained granite of the Lone Grove pluton. However, in general the rock is finer-grained and more distinctly non-seriate porphyritic. The groundmass has an average grain-size of 2 to 4 mm except in the extreme southeastern portion of the map area where it increases to 6 mm. The microcline phenocrysts have a maximum dimension ranging from 15 to 40 mm. Although they have not been mapped, many of the structural features found in the Lone Grove pluton may also be observed in this body.

In addition to the main plutons, numerous associated apophyses of coarse-grained granite occur within the country rock.

They are especially abundant in the Packsaddle schist near the western and southwestern margin of the Lone Grove pluton. These satellite intrusives range in size from tens of feet to several miles in length. Only the larger of these bodies are shown on Plate I. Several of the larger apophyses contain coarse-grained granite indistinguishable from that of the main intrusive. In other cases they contain a variety of texturally and chemically diversified rocks which probably represent some contamination of the magma by the host rock. All gradations of intrusive rock ranging from the typical coarse-grained granite to pegmatite, migmatite, and related hybrid material may be found near the border of the plutons.

Medium-grained granite:

Abruptly intruding the core of the pluton is a distinctly finer grained, reddish-pink granite. This medium-grained rock consists predominantly of quartz, microcline, plagioclase, and biotite. Accessory minerals are similar to those of the coarse-grained granite, but generally less abundant. Alteration of the biotite to chlorite and sericite is common in this rock and appears to be deuteric in nature. The rock is more acidic than the coarser-grained granite with mafic minerals making up less than 5% of it. The microcline of this rock shows practically no perthitic intergrowths of albite and is chemically quite close to stoichiometric potassium feldspar. The plagioclase is a sodic albite with well developed albite twinning. The quartz consists of anhedral, interlocking grains which are clear to slightly bubbly and contain minor amounts of zircon, apatite and mica crystallites. Brownish

biotite occurs as individual grains and aggregates throughout the rock. Although unaltered crystals are found, the biotite is commonly partially to completely altered to chlorite. Magnetite is commonly associated with the chloritized mica. Muscovite occurs both as discrete flakes and as sericitic patches associated with the biotite, plagioclase, and microcline. A minor amount of secondary carbonate also is present in the rock.

The grain size of this rock is distinctly finer than that of the coarse-grained granite. In general it ranges from 1 to 3 mm although coarser varieties are locally present. Occasional euhedral phenocrysts of microcline and more rarely quartz up to 30 mm in diameter are observed; however, their occurrence is much too sparse to call the rock porphyritic.

Although exposures of the contact between the coarse-grained and medium-grained granite are rarely observed, there appears to be a sharp contrast in lithologies between the two units. Wherever an outcrop of the actual contact does exist, the medium-grained granite shows an intrusive relationship with the coarse-grained granite. Locally, an abundance of quartz veins and pegmatite dikes occur at the boundary between these two rock types. In addition to the large stock of medium-grained granite intruding the core of the pluton, a smaller mass of similar material occurs to the west of it. Several dikes of medium- to fine-grained granite which may represent gradations between this rock and the late stage fine-grained granite and aplogranite are also scattered throughout the batholith.

The medium-grained granite is rather massive in texture. Although there is some evidence of flow foliation due to mineral alignment and an occasional oriented xenolith, the rock is much more uniform than the coarser-grained varieties. In general, the fabric displays a concentric pattern similar to that in the surrounding members of the pluton.

Fine-grained granite:

Intrusive into all the other members of the pluton as well as into the surrounding country rock are small stocks and dikes of fine-grained, pinkish-red to deep red, acidic granite and aplogranite. This rock consists of approximately equal amounts of quartz, microcline, and plagioclase with 1-3% chloritized biotite. Zircon, magnetite, apatite, and sphene are present as accessory minerals. Partial to complete deuteric alteration of biotite to chlorite and of sphene to leucoxene is commonly observed, while only a mild sericitization of the feldspar has occurred. The constituent minerals of the rock are subhedral to anhedral in shape and rather uniform in grain-size, giving the rock a distinctive sugary texture. Rare feldspar phenocrysts may be found; however, they are essentially absent in most of the rock.

This granite generally has a grain-size of 1 mm or less; however, it may locally grade into coarser-grained lenticules and pegmatitic stringers. Although a distinct contrast between the fine-grained granite and the medium-grained granite occurs in some outcrops, a complete gradation in lithology may be observed at other places. It is not possible to assign certain isolated

dikes of medium- to fine-grained leucocratic granite unambiguously to one or the other of these rock types. Locally, the rock becomes aphanitic in texture and may represent a rapidly chilled phase of this late-stage igneous activity. For purposes of mapping, the medium- and fine-grained granites have not been differentiated.

The contact between the fine-grained granite and the coarse-grained granite and surrounding metamorphic rocks is generally quite sharp. In most cases where exposures of this contact are present, the fine-grained granite is seen distinctly to cut the older rock. The chief exceptions lie in those places where the granite intrudes Valley Spring gneiss. The lithologies of these two rocks are generally quite similar and often the gneiss appears to grade into a massive, medium- to fine-grained granite simply by a loss in foliation. It is possible that this material is unrelated to the other granite; however, the rocks resemble each other in both texture and mineralogy.

Pegmatites and aplites:

Pegmatite and aplite dikes ranging from a few inches to several hundred feet in length are comonly encountered in the plutons. Most of the pegmatites consist predominantly of coarse, euhedral crystals of pink, perthitic microcline intergrown with massive bull quartz. These minerals may range from less than an inch to several feet in dimension. Biotite and, less commonly, fluorite, gadolinite, garnet, and a few other minerals may also be present. Miarolitic cavities are locally present in the pegmatites and contain euhedral crystals of smoky quartz, microcline,

and other minerals. In several cases the quartz and microcline show a well-developed graphic intergrowth in part of the pegmatite. An occasional more basic pegmatite, which contains, in addition to microcline, quartz, and biotite, crystals of hornblende and plagioclase up to a few inches in length, can also be found cutting the granite, as, for example, in the Petrick quarry.

The Baringer Hill pegmatite, famous for its abundance and variety of unusual rare-earth minerals, lies in the southeastern part of the Lone Grove pluton. This pegmatite, which was actively mined from 1887 to 1907 for its yttrium-bearing minerals, is now covered by Lake Buchanan. Detailed descriptions of it have been made by Hess (1908) and Landes (1932).

Muscovite is present in only a few pegmatites, most of which occur in the metamorphic rocks adjacent to the plutons. Occasionally, stringers of pegmatitic material found associated with the Valley Spring gneiss and, more rarely, the Packsaddle schist, especially near the contact of an intrusive body, contain booklets of muscovite in addition to quartz and microcline. The Badu pegmatite, which is located in the septum of schist separating the Lone Grove pluton from the Kingsland pluton, consists mainly of very coarse quartz and microcline; however, it contains delicate, rosette crystals of muscovite in clay-filled pockets. A description of this pegmatite is given by Barnes (1945).

Aplite dikes, many of which grade inward into pegmatite, are abundant in the coarse-grained granite. The aplite is pink

to gray in color, chiefly due to varying portions of microcline and biotite. It has a typically sugary texture and consists of subhedral to anhedral, equidimensional grains of calcic albite, quartz, and microcline with a subordinate amount of biotite and accessory fluorite and magnetite. The average grain-size of the rock is 1 to 3 mm although it may locally be coarser, especially where it lies adjacent to pegmatite.

The aplite appears to grade rather abruptly into the granite although nowhere is the contact knife-sharp. Locally, several generations of aplite can be seen to invade the same dike, and, thereby, give the rock a layered or banded structure. Near the center of a dike, the aplite may grade into quartz-microcline-biotite pegmatite. The chemical and petrologic relationships associated with one such aplite-pegmatite dike from the Petrick quarry has been described by Goldich (1941). In general, the aplite tends to be "dosodic" while the pegmatite is "dopotassic."

In general, the coarse-grained granite is host to rather sharply defined pegmatite and aplite dikes, while the medium- and fine-grained granites contain gradational lenses and stringers of pegmatitic material. There are, however, numerous exceptions to both these correlations. Although no rigid relationship was observed between the orientation of the pegmatites and aplites and the major structural features of the pluton, there appears to be a preponderance of these dikes lying either in the a-b or a-c direction. The former intrude approximately parallel to the concentric flow foliation and the latter form a radial pattern perpendicular

to the nearest margin of the pluton. In addition, numerous dikes having rather shallow dips and unrelated to any obvious structural direction were encountered. Many of the pegmatitic lenses occurring in the finer-grained granites are oriented parallel to local flowage directions. The concentration of pegmatites and quartz veins near the core boundary has already been mentioned.

Metamorphic rocks:

Two extensive areas of metamorphic rocks comprised of the Valley Spring gneiss and the Packsaddle formation crop out along the western and eastern margins of the Lone Grove and Kingsland plutons. A long, narrow septum of schist and marble from the Packsaddle formation separates these two intrusives from each other. Although the regional northwest-southeast trending structures are preserved at a distance from the plutons, most of the metamorphic rocks have been modified in the vicinity of the intrusives, especially where the contact lies at an angle to the original trend of the folds. Steeply dipping Packsaddle schist and Valley Spring gneiss are now observed in gross scale to wrap concordantly around the periphery of the granite except along the northern portion where overlying Paleozoic sediments mask the Pre-Cambrian rocks. In detail, the contact between the pluton and the country rock is more complicated and numerous examples of local cross-cutting relationships, apophyses, xenoliths, and lit-par-lit structure are present. Injection granite, pegmatite, and vein quartz associated with the major intrusives are often discernible in the schists and gneisses up to one mile or further from the contact.

Two periods of folding which predate the granite emplacement are present in the metamorphic rocks. An earlier period of almost isoclinal folding has deformed the rocks into a repetitious sequence of tight synclines and anticlines. Following this, the entire area was refolded along northwest-southeast trending axes into broad, open synclinoria and anticlinoria. It is these major structures which today expose Valley Spring gneiss along the cores of the anticlinoria and preserve Packsaddle formation in the downfolded synclinoria. Paige (1912) shows one of these major anticlinorial axes extending through a large outcrop of Valley Spring gneiss, a part of which is exposed along the western margin of the map area. Although the regional structure becomes less clear near the major plutons, the preponderance of Packsaddle schist along the contacts with these bodies suggests that this region may be synclinal in nature. Several of the other intrusions of the uplift are more clearly related to such synclinal structures. The gneisses and schists within the map area are often folded into complicated structures, the grosser details of which are shown on Plate I.

The rocks have all undergone a regional metamorphism of medium rank except in local areas where contact phenomena have developed somewhat higher grade mineral assemblages. Field evidence shows that this regional metamorphism predates the granite intrusions, but there is no indication of the time interval separating these two events.

The Valley Spring gneiss consists predominantly of interlocking grains of quartz, microcline, and plagioclase (An_8 to

An_{30}). Biotite is essentially ubiquitous and generally makes up several percent of the rock. Magnetite, apatite, and sphene are almost always present as accessory minerals, and hornblende, fluorite, calcite, and rutile have been observed in several specimens. The gneiss is pink to gray in color depending on the relative abundances of feldspar and biotite. Minor layers of quartzite, calc-silicate rock, and biotite schist are included in the formation; however, the lithology of the Valley Spring gneiss is much more monotonous than that of the Packsaddle formation. The gneiss ranges in average grain-size from less than 0.1 mm to 2 mm, and, in addition, may contain local, much coarser, pegmatitic development. Texturally, the gneiss varies from well foliated with distinctive gneissoid banding to almost massive. It is generally fairly resistant to weathering and forms a hummocky topography. Occasional highly resistant units form prominent peaks which rise several hundred feet above the surrounding terrane. Niggerhead Peak, northeast of Buchanan Dam, and Lockhart Mountain, northwest of Lone Grove, are examples of areas underlain by this resistant gneiss.

The Packsaddle formation contains mica and graphite schist, amphibolite, marble, calc-silicate rock, and gneiss. Most of the rock displays a well-developed foliation which parallels lithologic units. Although no continuous section more than a few hundred feet thick was measured, it is probable that several thousand feet of the formation are present within the map area. Biotite schist is the predominant rock type in the Packsaddle formation,

while graphite schist, carbonate, amphibolite, and gneissoid rocks each make up less than 10% of it. These latter lithologies generally occur in beds several feet to tens of feet in thickness. The Packsaddle formation forms the steeply dipping, concordant wall rock around most of the exposed Lone Grove and Kingsland plutons. Migmatite is commonly developed adjacent to the intrusions where granitic material has been intimately intruded into the schist. The schists are composed of quartz, microcline, and biotite with or without plagioclase, hornblende, and muscovite. Accessory apatite, sphene, and magnetite are present in most of the rocks, and graphite occurs in amounts up to several percent in the graphitic phases. The amphibolites consist mainly of andesine, hornblende, and quartz with minor biotite and magnetite. The schists and amphibolites are generally fine-grained and well-foliated. Fine- to coarse-grained calcite and dolomite marbles and calc-silicate rock containing, in addition to carbonate, tremolite, wollastonite, diopside, and graphite are recurrent in the Packsaddle formation. The schists are rather susceptible to weathering and form a terrane of low relief. They are somewhat more resistant, however, than the coarse-grained granite, and, therefore, the septum of Packsaddle formation which separates the Lone Grove and Kingsland plutons forms a low topographic ridge.

Paleozoic sediments:

Unmetamorphosed, flat-lying Paleozoic sedimentary rocks, chiefly of Upper Cambrian and Lower Ordovician age, cover the northern quarter of the map area and also occur elsewhere as

isolated grabens and outliers. These remnants of a sedimentary cover which once extended over the entire Llano Uplift indicate that the present land surface of the basement rocks lies near that of an exhumed Upper Cambrian surface. Thus, the metamorphic and igneous rocks used in this study come from only a few tens or, at the most, hundreds of feet below an ancient erosion surface which existed for an unknown duration of time. Although the details of this surface are poorly known, domical hills having local reliefs of up to several hundred feet rose above the general land level. Structures related to some of these domes, which are now completely or partially buried by overlying Paleozoic sediments, have been described by Barnes (1956) in a study of lead and zinc mineralization associated with them. Also, the basal Upper Cambrian Riley formation, which is one of the important aquifers of central Texas, has covered this area for the last five hundred million years, and may have circulated ground water just a short distance above the presently exposed basement rocks. One must, therefore, consider the possibility of meteoric effects upon the rocks under investigation.

The sedimentary and underlying basement rocks have been broken by numerous high-angle, normal faults which are of probable Late Paleozoic age. In general, two sets of faults, one trending roughly northeast-southwest and the other trending north-south, are present within the Uplift. Displacements ranging from several feet to hundreds of feet are measurable where the faults cut the known Paleozoic succession. Although it is more difficult to detect

these faults in the Pre-Cambrian rocks, a comparable fault density and amount of displacement is probably present. Occasionally, mylonitic zones and discontinuous structures within the basement attest to such faulting. Only the major faults within the map area are shown on Plate I.

EXPERIMENTAL PROCEDURE

Mineral Separation

Material for petrologic study and mineral analysis was collected from each of the sample localities during the falls of 1960 and 1961. Each rock was examined in thin section to determine the minerals present. Except for the pegmatitic minerals and the feldspar from the rhyolite porphyry which were processed by hand, the rock was crushed in a Braun chipmunk crusher and pulverizer and the resultant material sized through a series of brass screens. The size fraction considered most advantageous for obtaining a given mineral separate was then further processed. Material for total rock analyses was ground to -80 mesh and the entire sample was taken.

Mineral separation was obtained through the use of tetrabromoethane and diiodomethane heavy liquids and the Frantz isodynamic magnetic separator. Strongly magnetic fragments consisting chiefly of steel splinters from the crushing apparatus were removed prior to this with a hand magnet. A final purification of some micas was obtained by sliding the material across an inclined sheet of paper. Modal analyses were made using grain mount and oil immersion techniques to determine the purity of the final mineral separates, and these results are given in Table 7. Splits of the mineral separates for use in the chemical and isotopic analyses were obtained by passing the material through a 6" two-way, joint-free, aluminum sample splitter (McKinney and Silver, 1956).

Rubidium-strontium Analysis

All rubidium and strontium determinations were made employing the techniques of isotope dilution and mass spectrometry. The procedure followed was similar to that developed at the Carnegie Institution of Washington. Sample splits of 0.2 to 0.5 g were weighed and placed into a clean platinum crucible. Approximately 8 ml of 48% HF and 2 ml of $HClO_4$ were added and the crucible was placed on a warm hot-plate to digest. When the perchloric acid began to fume, the heat was increased and the residue taken almost to dryness. Apatites were dissolved in 5 ml HNO_3 and likewise evaporated almost to dryness. 20 to 30 ml of triple-distilled water was then added and the sample taken into solution.

Approximate concentrations of rubidium and strontium were determined beforehand on each mineral separate by x-ray fluorescence in order to estimate the quantity of spike to be added. Where an enrichment in radiogenic Sr^{87} of over 20% was expected, a weighed quantity of the Sr spike solution was added to the dissolved mineral at this time. The solution was transferred to a 150 ml pyrex beaker and diluted with distilled water to about 100 ml. This solution was then thoroughly stirred prior to removing a 2-6% rubidium aliquot in order to eliminate inhomogeneities which would seriously affect the rubidium determination. The rubidium portion was transferred to a 15 ml pyrex beaker for spiking with the Rb spike solution. Both spiked solutions were placed on the hot-plate and evaporated to dryness. The residue from the rubidium aliquot was loaded directly on the source filament for mass spectrometric analysis

without further chemical purification. The strontium residue was taken up in 2 ml of 2.5N HCl and the accompanying particulate matter removed by centrifuge. The supernatant liquid was transferred to an ion exchange column containing 15 ml of 50-X8 200-400 mesh Dowex resin which had been backwashed with 2.5N HCl. The column was then eluted with 2.5N HCl and the appropriate strontium-containing fraction retained and evaporated to dryness for mass spectrometric analysis. The column was stripped after every separation with 100 ml 6N HCl. Both the 2.5N and 6N HCl were prepared by passing HCl gas through triple-distilled water until the desired normality was acquired.

In those cases where a strontium compositional analysis was also required, the spiking procedure was slightly altered in order to remove first a quantity of the solution for this purpose before the tracer was added. Ion exchange purification of the strontium composition fraction was carried out similarly to that for the strontium spiked fraction.

All pyrex and platinum ware were boiled in nitric acid and distilled water before each use. Small 15 ml and 5 ml pyrex beakers were discarded after one use in order to prevent cross contamination.

The reagents used in this work were analyzed for their rubidium and strontium contents. In addition, blank runs were made in order to determine the level of contamination to be expected. These results, as well as the potassium concentrations, are given in Table 1. It can be seen that the contributions from

Table 1. (a) Reagent Analyses for Rubidium, Strontium, and Potassium.

Reagent	Rb, ppb	Sr, ppb	K, ppb
HF	--	--	40
$HClO_4$	0.75	8.1	70
2.5N HCl	--	0.10	--
6N HCl	--	0.10	--
H_2SO_4	--	--	20
H_2O	0.05	0.10	10

(b) Blank Runs Performed under Similar Conditions to a Mineral Analysis.

Blank	Rb, μg	Sr, μg	K, μg
I	0.008	0.2	--
II	--	--	5

contaminants to those minerals on which Rb-Sr ages were determined were negligible in all cases, and only a few common strontium minerals required a significant correction.

The rubidium and strontium tracers used in these analyses were prepared from material obtained from Oak Ridge National Laboratories. The salts were dissolved in 2N HCl solutions and stored in polyethylene bottles. Gravimetrically prepared solutions of spectroscopically pure normal strontium and rubidium were used to calibrate the spike solutions. The composition of the Sr tracer in atom percent is Sr^{88} = 14.4%, Sr^{87} = 2.10%, Sr^{86} = 83.5%, and Sr^{84} = 0.0157% and the solution contains $0.0155_5 \pm 0.0000_8$ μmoles Sr^{86}/g solution. The composition of the Rb tracer in atom percent is Rb^{87} = 95.42% and Rb^{85} = 4.58% and the solution contains 3.30 ± 0.03 μg Rb/g solution.

Potassium Analysis

With the exception of quartz, all minerals were analyzed for potassium by flame photometry. In addition, the hornblendes and two biotites were also analyzed by isotope dilution. The potassium content of the quartz was determined only by isotope dilution. The chemistry for both these techniques was identical and aliquots from the same solution were used where the two methods were employed on a particular sample. Sample splits of 0.3 to 1.0 g were weighed and dissolved by 8 ml HF and 2 ml H_2SO_4 in a platinum crucible. After digestion 1 ml HNO_3 was added and the sample evaporated to near dryness. It was then taken back into

solution with distilled water and diluted to 250 ml.

The flame photometric analyses were carried out following the procedure of Shapiro and Brannock (1956). Solutions using a 200 ppm Li internal standard in the final solution were run on a Perkin-Elmer instrument. Ten sets of readings were taken and the average potassium concentration determined. The mean deviation of a single analysis was usually better than ± 0.3%. Repeat analyses on several solutions gave potassium values reproducible to ± 0.5% throughout the concentration range encountered in this study. Numerous experiments designed to observe the effects of interfering cations and anions showed no detectable suppression or enhancement of the potassium under the conditions of these analyses (Wasserburg, Zartman, and Wen, in press).

Where isotope dilution was also employed, aliquots of the original solutions were spiked with a tracer having an isotopic composition of $K^{39}:K^{40}:K^{41}::74:100:1000$. This enabled the discrimination of the mass spectrometer to be determined in each experiment from the ratios in the mixture of sample and spike. The spiked solution was evaporated to dryness and the residue loaded directly on mass spectrometer source filament without further chemical purification.

The potassium tracer was prepared similarly to the rubidium and strontium spike solutions, and calibrated against spectroscopically pure normal potassium solutions. The composition of the K tracer in atom percent is $K^{41} = 85.22\%$, $K^{40} = 8.52\%$, and $K^{39} = 6.26\%$ and the solution contains $0.289_4 \pm 0.001_5$ μmoles

K^{41}/g solution.

No significant discrepancy between the two methods of potassium analysis was found in any of the experiments (Wasserburg, Zartman, and Wen, 1962). The results obtained by flame photometry and isotope dilution were averaged together in order to obtain the potassium value used in the age determinations. The problem of sample inhomogeneity between separate sample splits is independent of the analysis of a particular solution. Since the argon extraction is made on a different portion of the mineral separate, it is important to obtain a representative split in determining the potassium. This problem becomes most acute in the case of a low potassium mineral containing a high potassium contaminant such as hornblende with included biotite. Several splits of the hornblende separate from the Petrick quarry granite (3gr) were analyzed for potassium and found to contain variations of over 2% between different splits. It is most probable that this effect is due to slightly different amounts of contaminating biotite in the material. Whenever repeat analyses were made on an essentially pure mineral, variations of more than 1% were not observed.

Argon Extraction

The argon extraction was accomplished through direct fusion of the mineral by using a 10-kilowatt radio-frequency induction heater. Sample splits of 2 to 7 g were loaded in a molybdenum crucible and placed into a quartz reaction vessel surrounded by a water jacket and the primary windings of the induction coil. The reaction vessel was attached to a gas purification train

through a steel flange which seats on a copper gasket. The extraction system with the exception of the reaction vessel was baked out overnight in a marinite oven and the entire line leak tested prior to every run.

An argon spike release was pipetted into the system from the tracer reservoir and frozen out with liquid nitrogen on a charcoal trap. The induction heater was then slowly brought to a maximum temperature of 1400-1500° C producing a complete fusion of the sample.* The evolved gases were thoroughly mixed with the spike by repeatedly freezing and thawing them on charcoal with liquid nitrogen. They were passed in turn over a CuO and a Ti furnace until optimum cleanup was obtained. The residual pressure was monitored with a McLeod gauge, and the final gas, consisting mainly of argon, was frozen out with liquid nitrogen on a charcoal sample tube for transfer to the mass spectrometer.

The argon tracer was obtained from Oak Ridge National Laboratories; it has a Ar^{40}/Ar^{38} ratio of 0.124_0 and a Ar^{36}/Ar^{38} ratio of 0.00124. The tracer is held in a two liter reservoir and is released into the extraction line through a 3.40 ml mercury cutoff gas pipette. The decay constant of the reservoir has been determined to be 0.157 percent per release and the amount of tracer used throughout the work ranged from 1.0 to 0.8×10^{-4} ccSTP of Ar^{38}. The tracer was calibrated periodically by isotope dilution with known amounts of spectroscopically pure normal argon measured on a micro-McLeod. These calibrations, which extended

*A repeat extraction on a biotite sample initially yielding 10^{-3} ccSTP of radiogenic argon gave less than 5×10^{-7} ccSTP on the second run.

over approximately 150 spike releases, were consistent with the calculated tracer concentration for the given release to better than ± 0.8%. A similar tracer system has been described by Wasserburg, Wetherill, Silver, and Flawn (1962).

Mass Spectrometry

The rubidium, strontium, and potassium isotopic analyses were run on a 12" radius of curvature, 60° sector, single focusing, solid source mass spectrometer described by Chow and McKinney (1956). All samples were run employing the single filament, surface ionization technique. The filament block and first two source plates were removed after each run and thoroughly cleaned in hot nitric acid and distilled water. A filament (.001" x 0.030") of tantalum ribbon was spot welded to kovar pins and mounted on the filament block. The filament was outgassed before rubidium and potassium runs in order to remove trace impurities of these elements from the tantalum ribbon. The sample was taken up in a drop of distilled water and transferred to the filament with a clean, glass capillary tube attached to a hypodermic syringe. After loading the source assemblage into the mass spectrometer, the filament was heated for several hours just below the ionization temperature in order to burn off the more volatile material and stabilize emission conditions. During operation, the ion beam was accelerated by a 5 kilovolt potential and magnetic scanning used. The resolved beam entered the collector slit and impinged upon the conversion dynode of a ten-stage

silver-magnesium electron multiplier. The resultant current then passed across a 2×10^{9} ohm resistor and a vibrating reed electrometer, which, in turn, drove a recording pen on a strip chart. Ion currents of 10^{-14} to 10^{-12} amperes were obtained in most of the runs.

The argon isotopic analyses were run on a 6" radius of curvature, 60° sector, single focusing, Nier-type mass spectrometer (Nier, 1947). Design modifications by C. R. McKinney and G. J. Wasserburg included a 52° magnet for z focusing. All samples were run dynamically by allowing the gas to enter the source box by way of a molecular leak and then be pumped away. An adjustable, mercury-filled reservoir was used to regulate the gas flow through the leak. The ion beam was accelerated through a 4 kilovolt potential and scanning was accomplished by varying the magnetic field with a resistance-capacitance circuit. The resolved beam entered one of two collector systems, a single Faraday cage or a ten-stage Dumont copper-beryllium electron multiplier. The multiplier was operated at 250 volts per stage with a gain of approximately 2000. The current passed through a 10^{10} or 10^{11} ohm resistor on the simple collector or a 10^{9} or 10^{10} ohm resistor on the multiplier and was amplified by a vibrating reed electrometer which drove a recording pen on a strip chart. Ion currents of 10^{-12} to 10^{-11} amperes were obtained for the mass 40 and 38 signals, while the mass 36 signal was generally less than 10^{-14} amperes. Background corrections were negligible except for mass 36 where 10% or less of the peak

height was due to contaminants in the mass spectrometer.

Precision and Accuracy

In evaluating the results of these analyses, it is important to establish the limits of experimental error. An estimate of the precision or reproducibility of each determination is necessary in order to distinguish real differences from analytical uncertainties. It is also important to have a knowledge of the accuracy or correctness of the analyses.

The precision attainable in a given isotope analysis depends upon uncertainties in sample homogeneity, chemistry, isotope dilution, and mass spectrometry. In argon extractions, the sample fusion and clean-up are analogous to the chemistry in rubidium, strontium, and potassium determinations. Uncertainties in flame photometry affect the potassium analyses done by that method. Although a definite evaluation of these various sources of error is rather difficult, it is believed that careful work in sample preparation, chemical processing, and spiking lead to uncertainties in these steps of only a few tenths of a percent. The only exceptions appear to be sample inhomogeneity in the case of certain hornblende separates with slightly varying amounts of contaminant biotite leading to as much as 2% differences between determinations, and a few 'common' strontium minerals in which the rubidium content is near the blank level.

The greatest source of uncertainty in the isotope dilution method occurs in the mass spectrometry. Normal rubidium, strontium, potassium, and argon samples were run frequently

during the duration of this work in order to monitor mass discrimination. Unpredictable variations in discrimination producing uncertainties of a percent or more in the analyses were observed for all elements. Variations of up to 5% per two mass units occur in the potassium analyses; however, this effect can be corrected by normalizing the K^{40}/K^{41} ratio of the spike. The rubidium and strontium show a more consistent behavior with extreme variations in discrimination of $1\frac{1}{2}$ and 1% per two mass units, respectively. When strontium compositional analyses are made, the Sr^{88}/Sr^{86} ratio is normalized in order to minimize this uncertainty. The argon shows an uncertainty of approximately $1\frac{1}{2}$% in the Ar^{40}/Ar^{36} ratio which introduces an effect of 3/4% into the analyses. The actual reading error of the strip chart is generally less than ± 0.2%.

Flame photometry also introduces the greatest error in those potassium analyses done by this method; in general, this effect is considered to be less than 1% over the concentration range encountered in this work.

The combined sources of error lead to uncertainties in the precision of the analyses of approximately ± 1% for rubidium and potassium, ± 3/4% for highly radiogenic strontium, and ± 1% for highly radiogenic argon. The errors assigned to each analysis given in Tables 2 and 3 represent the estimated precision for that determination.

Five separate Rb^{87}-Sr^{87} and K^{40}-Ar^{40} determinations were made on the biotite from the Petrick quarry granite (3gr)

during the course of the study. The analyses gave rubidium and radiogenic strontium concentrations which fell within a range of 2% and Rb^{87}-Sr^{87} ages within a range of 1% (see Table 2). The fifth determination was made by spiking the entire sample for rubidium in order to check inhomogeneity in the aliquot procedure. The argon concentrations fell within a range of 2% which produced a $1\frac{1}{2}$% spread in the K^{40}-Ar^{40} age (see Table 3). This is within the expected analytical error of both the chemistry and the mass spectrometry, and gives an indication of the precision obtainable by these techniques.

In addition to the limits of precision, the accuracy of the isotope dilution analyses are dependent upon the correctness to which the tracer concentrations are known. As previously described, all tracers have been calibrated with carefully prepared normal standards. Thus, the determination of the tracer concentrations is simply a reverse spiking procedure and the same levels of precision prevail as in an analysis. The absolute concentrations of the normal solutions of rubidium, strontium, and potassium are believed to be known to a few tenths of a percent, and the standard volumes of normal argon to a half of a percent. Several tracer calibrations were made for each element and the resultant values of the concentrations were reproducible to ±1% in all cases.

The accuracy of the potassium flame photometric analyses is dependent upon the internal standards and biases arising from interference effects. A thorough investigation of the flame

photometry technique suggests that accuracies of ±1% are obtained on minerals within the potassium concentration range encountered in this study.

For all the reported analyses, the values given are believed to be accurate to within ± 1% over the stated precision error. The daughter to parent ratios would, therefore, be accurate to within ± 2% over the combined precisions.

In addition, the absolute values of the ages are dependent upon the accuracy with which the decay constants are known. An evaluation of these constants is beyond the scope of this work.

DISCUSSION OF RESULTS

Geochronological Data

Age determinations were made on one or more mineral separates from 13 localities throughout the Lone Grove pluton and other major lithologies in the Uplift. The analytical results for the Rb^{87}-Sr^{87} and the K^{40}-Ar^{40} ages are presented in Tables 2 and 3, respectively. When several determinations on a single mineral separate are given, each result represents a complete analysis on a different split of the master sample.

These data represent the raw results obtained on individual mineral separates and have not been corrected to the pure mineral composition. In most cases, the separates were of such purity that contributions from contaminating minerals are negligible; however, in several cases, particularly those involving biotite in hornblende separates, appreciable corrections are necessary in order to calculate pure mineral compositions. In the later section on the distribution of elements between the various mineral phases and different sample localities, corrections to pure mineral compositions have been made and will be discussed at that time.

A detailed discussion of the error given for each analytical determination is presented in the preceding section on Experimental Procedure.[1] The corresponding error assigned

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[1] It should be emphasized that uncertainties in the absolute tracer concentrations are not included in the analytical error. Since all samples have been analyzed with a common tracer for each element, comparisons of precision between individual minerals are independent of the actual tracer concentration.

Table 2. Rb^{87}-Sr^{87} Ages of Rocks from the Llano Uplift, Texas.

Rock	Mineral	Rb^{87}, ppm	Sr^{87*}, ppm	$\frac{Sr^{87*}}{Sr^{87}_{total}}$	Age, my
3gr	micr	91.9 ± 0.9	1.36 ± .08	0.11	995 ± 70
			1.42 ± .03†	0.109	1040 ± 30
	bio	227 ± 2	3.43 ± .03	0.85	1015 ± 15
		228 ± 2	3.43 ± .03	0.85	1010 ± 15
		227 ± 2	3.44 ± .03	0.87	1020 ± 15
		226 ± 2	3.39 ± .03	0.83	1010 ± 15
		227 ± 2	3.40 ± .03	0.86	1010 ± 15
	TR	45.0 ± 0.5	0.68 ± .06	0.08	1015 ± 95
			0.67 ± .02†	0.084	1000 ± 40
3ap	TR	121 ± 1	1.82 ± .0	0.76	1010 ± 20
3p-1	micr	149 ± 1	2.30 ± .03	0.63	1040 ± 20
	bio	658 ± 7	7.99 ± .06	0.98	820 ± 15
		568 ± 6	7.07 ± .05	0.97	840 ± 15
3p-2	bio	713 ± 7	8.91 ± .07	0.98	840 ± 15
3p-3	micr	139 ± 1	2.12 ± .03	0.47	1020 ± 25
	bio	663 ± 7	6.44 ± .05	0.89	655 ± 10
3p-4	micr	111 ± 1	1.66 ± .03	0.33	1005 ± 25
	bio	421 ± 4	5.98 ± .04	0.95	955 ± 15
50gr	micr	77.1 ± 0.8	1.13 ± .10	0.07	985 ± 100
			1.15 ± .04†	0.069	1005 ± 45
	bio	170 ± 2	2.58 ± .02	0.78	1020 ± 20
41gr	micr	83.8 ± 0.8	1.29 ± .10	0.08	1035 ± 90
			1.30 ± .04†	0.086	1045 ± 40
	bio	212 ± 2	3.07 ± .02	0.68	975 ± 20

Table 2 (Cont'd)

Rock	Mineral	Rb^{87}, ppm	Sr^{87*}, ppm	$\frac{Sr^{87*}}{Sr^{87}_{total}}$	Age, my
128gr	micr	118 ± 1	1.72 ± .06	0.17	985 ± 45
			1.76 ± .03†	0.173	1005 ± 25
	bio	310 ± 3	4.63 ± .04	0.92	1005 ± 15
128Wgr	micr	109 ± 1	1.69 + .06	0.15	1040 ± 50
			1.62 ± .03†	0.146	1000 ± 25
	bio	292 ± 3	4.15 ± .04	0.89	955 ± 20
149gr	micr	71.9 ± 0.7	1.11 ± .10	0.06	1040 ± 100
			1.07 ± .04†	0.064	1000 ± 45
	bio	167 ± 1	2.30 ± .02	0.70	925 ± 20
221gr	micr	97.8 ± 1	1.46 ± .06	0.13	1005 ± 55
			1.51 ± .03†	0.140	1040 ± 25
	bio	413 ± 4	4.47 ± .04	0.92	730 ± 15
	TR	80.7 ± .08	1.14 ± .04	0.17	950 ± 50
			1.15 ± .02†	0.166	960 ± 25
22IIgr	micr	102 ± 1	1.54 ± .06	0.14	1015 ± 55
			1.59 ± .03†	0.144	1050 ± 25
	bio	438 ± 4	4.36 ± .04	0.93	665 ± 15
4gr	micr	243 ± 2	3.66 ± .03	0.47	1015 ± 20
	musc	273 ± 3	4.37 ± .04	0.55	1075 ± 20
	bio	283 ± 3	4.31 ± .04	0.72	1025 ± 20
6gr	micr	92.7 ± 0.9	1.32 ± .10	0.09	960 ± 85
			1.35 ± .04†	0.090	980 ± 40
	bio	264 ± 3	3.99 ± .03	0.84	1015 ± 15

Table 2 (Cont'd)

Rock	Mineral	Rb^{87}, ppm	Sr^{87*}, ppm	$\frac{Sr^{87*}}{Sr^{87}_{total}}$	Age, my
20gr	micr	72.0 ± 0.7	1.09 ± 0.6	0.10	1020 ± 70
			1.10 ± .03†	0.101	1030 ± 30
	musc	83.2 ± 0.8	1.28 ± .04	0.48	1035 ± 20
	bio	160 ± 2	2.44 ± .02	0.85	1020 ± 15
21p	musc	164 ± 2	2.53 ± .02	0.88	1040 ± 15
53gn	micr	118 ± 1	1.84 ± .06	0.16	1050 ± 50
			1.87 ± .03†	0.160	1065 ± 25
	bio	284 ± 3	4.32 ± .04	0.78	1025 ± 20
14rp-1	micr	92.3 ± 0.9	1.27 ± .05	0.13	925 ± 55
			1.28 ± .03†	0.125	935 ± 25
14rp-2	micr	85.0 ± 0.9	1.11 ± .04	0.18	890 ± 45
			1.11 ± .02†	0.185	890 ± 20

† strontium composition analysis

Table 3. K^{40}-Ar^{40} Ages of Rocks from the Llano Uplift, Texas.

Rock	Mineral	K^{40}, ppm	A^{40*}, ppm(±1%)	$\frac{A^{40*}}{A^{40}_{total}}$	Age, my
3gr	micr	13.11 ± .04	0.982	0.99	975 ± 10
	olig	0.50_9 ± $.00_6$	0.036_5	0.88	945 ± 20
	bio	7.38 ± .03	0.603	0.98	1045 ± 10
			0.601	0.98	1040 ± 10
			0.600	0.98	1040 ± 10
			0.606	0.99	1050 ± 10
			0.612	0.99	1055 ± 10
	hb	2.07 ± .03	0.170_7	0.98	1050 ± 20
3p-1	micr	11.29 ± .03	0.806	0.98	940 ± 10
	bio	8.41 ± .03	0.605	0.96	945 ± 10
3p-2	bio	8.96 ± .03	0.673	0.97	980 ± 10
3p-3	bio	8.13 ± .03	0.478	0.95	805 ± 10
3p-4	olig	0.54_0 ± $.00_7$	0.034_3	0.91	855 ± 20
	bio	8.72 ± .03	0.670	0.97	995 ± 10
	hb	1.45 ± .02	0.122_8	0.99	1075 ± 20
50gr	micr	13.76 ± .04	0.990	0.98	945 ± 10
	bio	7.12 ± .03	0.586	0.99	1050 ± 10
	hb	2.38 ± .03	0.178_7	0.98	980 ± 20
41gr	bio	7.69 ± .03	0.612	0.98	1025 ± 10
	hb	2.28 ± .03	0.194_7	0.99	1080 ± 20

Table 3 (Cont'd)

Rock	Mineral	K^{40}, ppm	A^{40*}, ppm(±1%)	$\frac{A^{40*}}{A^{40}_{total}}$	Age, my
128gr	bio	8.57 ± .03	0.706	0.98	1050 ± 10
	hb	1.47 ± .02	0.119_7	0.98	1040 ± 20
128Wgr	bio	8.31 ± .03	0.676	0.98	1040 ± 10
	hb	1.50 ± .02	0.120_5	0.97	1030 ± 20
149gr	bio	8.26 ± .03	0.663	0.99	1030 ± 10
	hb	2.31 ± .03	0.195_5	0.98	1075 ± 20
22Igr	bio	9.25 ± .03	0.758	0.99	1045 ± 10
22IIgr	bio	9.21 ± .03	0.744	0.99	1035 ± 10
4gr	micr	15.64 ± .04	1.079	0.99	915 ± 10
	musc	8.21 ± .03	0.650	0.98	1020 ± 10
	bio	4.71 ± .02	0.385	0.99	1045 ± 10
6gr	bio	8.88 ± .03	0.728	0.98	1045 ± 10
20gr	musc	9.58 ± .03	0.818	0.98	1080 ± 10
	bio	7.79 ± .03	0.660	0.99	1075 ± 10
21p	musc	10.31 ± .03	0.872	0.98	1075 ± 10
53gr	micr	14.54 ± .04	1.100	0.99	985 ± 10
	bio	9.04 ± .03	0.728	0.99	1035 ± 10
25am	hb	$0.29_9 \pm .00_3$	0.024_1	0.92	1035 ± 15

to the age represents that obtained by the most unfavorable conjunction of parent and daughter isotope uncertainties. It does not include any errors which may arise from uncertainties in the half-lives or geochemical history of the sample.

Rubidium-strontium ages have been calculated using a decay constant for Rb^{87} of 1.47×10^{-11} $years^{-1}$ (Flynn and Glendenin, 1959). This is 6% greater than the decay constant of 1.39×10^{-11} $years^{-1}$ proposed by Aldrich and Wetherill (1958). All of the Rb^{87}-Sr^{87} ages would uniformly become 6% larger if the smaller decay constant were used. The abundance of Rb^{87} in atom percent is taken to be 27.85% (Nier, 1950a). Ages on minerals with a radiogenic Sr^{87} enrichment of less than 20% were determined by running the mineral strontium composition. The Sr^{86}/Sr^{88} ratio was then normalized to 0.1194 and the corresponding Sr^{87}/Sr^{88} obtained (P. W. Gast, personal communication). The Sr^{87}/Sr^{88} ratio of the strontium incorporated into the original minerals is taken to be 0.0843 ± 0.0002, the average value obtained from analyzing several common strontium minerals (see Table 6).

The K^{40} decay constants used in calculating the potassium^{40}-argon^{40} ages are $\lambda_\beta = 4.72 \times 10^{-10}$ $years^{-1}$ and $\lambda_e = 0.585 \times 10^{-10}$ $years^{-1}$ (Aldrich and Wetherill, 1958). The abundance of K^{40} in atom percent is taken to be 0.0119% (Nier, 1950b).

Errors of at least a few percent may still exist in the experimental values of the Rb^{87} and K^{40} decay constants. Therefore,

meaningful direct comparisons of ages between the Rb^{87}-Sr^{87} and K^{40}-Ar^{40} methods cannot be made to a greater precision than is inherent in this uncertainty. On the other hand, a relative comparison of ages between these two geochronological systems is essentially independent of the decay constants, and limited only by the analytical errors of the determination.

The sample localities of the materials used in this study are shown in Figure 1 and Plate I. Petrological descriptions of each of the rocks are given in the Appendix. In order to study the ages and element distribution between the various lithologies of the Lone Grove pluton, samples were obtained and analyzed from the different granites and associated pegmatites and aplites of the intrusive. Six samples of coarse-grained, Town Mountain granite (3gr, 50gr, 41gr, 128gr, 128Wgr, and 149gr), one of coarse-grained, foliated granite (22gr), one of medium-grained granite (4gr), one of aplite (3ap), and a suite of pegmatites (3p) were used. The sample localities were the best quarry and road-cut exposures available in the pluton and also represented a good areal sampling of it. Most of the material represented the freshest looking rock available at a given locality. Samples of granite from near the Cambrian erosion surface (149gr) and from the present erosion surface in the Texas quarry (128Wgr) were specifically collected to study the effects of weathering on the mineral ages.

Analyses were also made on several of the other major igneous and metamorphic rocks of the Uplift. Samples of the

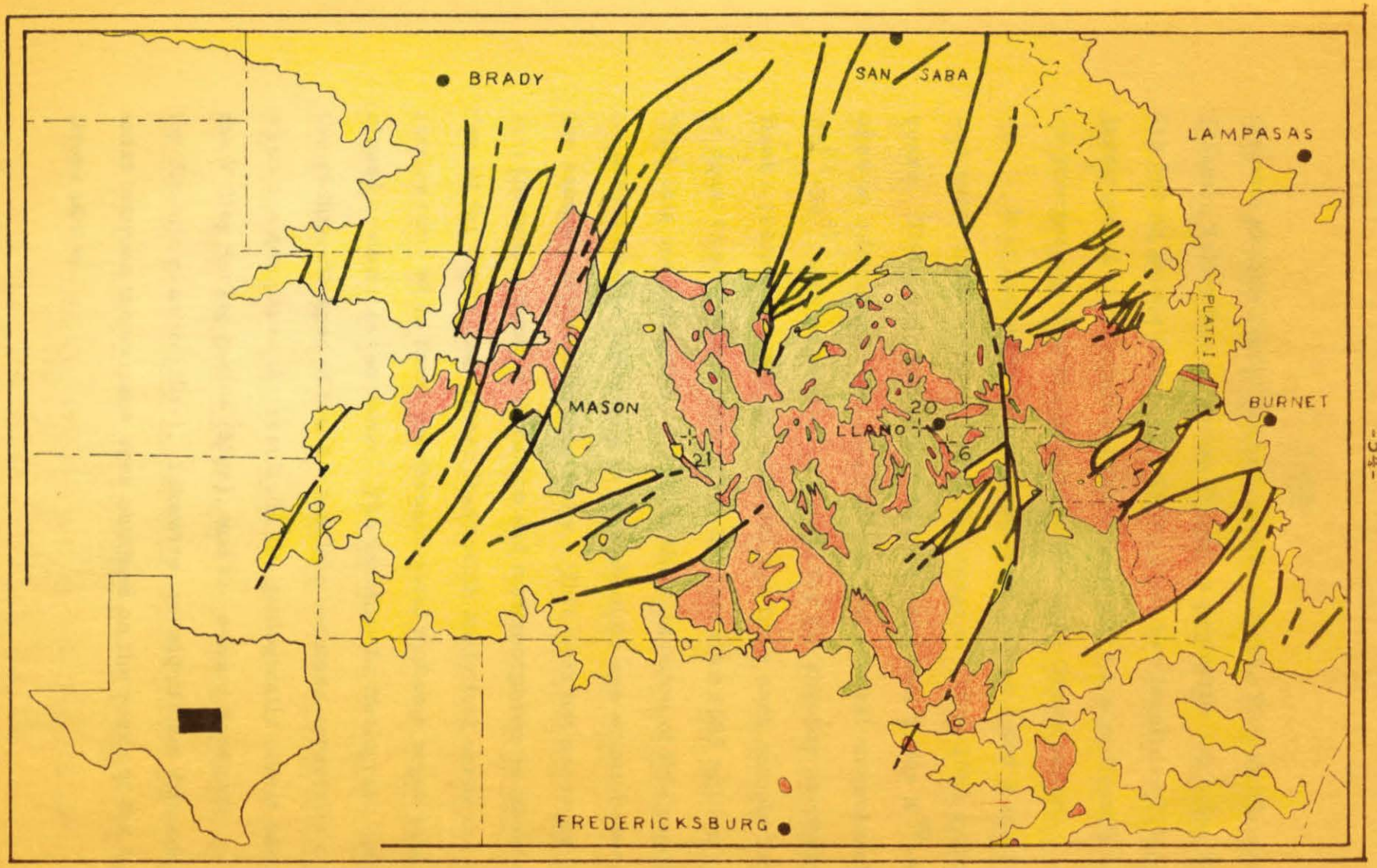

Fig. 1. Geologic map of the Llano Uplift (scale 1" ≃ 12 miles). Explanation: red, pЄ granite; green, pЄ metamorphic rocks; yellow, Paleozoic sediments; uncolored, Cretaceous sediments. Shows sample localities not included within Plate I. (generalized from Geologic Map of Texas, U.S.G.S., 1937).

Oatman granite (6gr), Sixmile granite (20gr), Packsaddle formation (25am), Valley Spring gneiss (53gn), a pegmatite intruding the Valley Spring gneiss (21p), and llanite from two localities (14rp) were investigated to determine if these units gave a significantly older or younger age than the granite of the Lone Grove pluton.

It is immediately apparent from Tables 2 and 3 and Plate II that most of the ages lie within the range of 980 to 1080 million years. The major exceptions involve somewhat lower K^{40}-Ar^{40} ages on microclines and plagioclases and several anomalously low Rb^{87}-Sr^{87} ages on biotites. Except for the rhyolite porphyry, or llanite (14rp), at least one mineral age from each sample locality is equal to or greater than 1030, but less than 1085 million years. With this one exception, it will be the contention of this paper that no demonstrable difference in true absolute age exists between the samples included in this study. This does not necessarily mean that the actual time of intrusion and metamorphism is identical for all the rocks, but rather that within analytical error the effective time when these geochronological systems began to act as closed systems is the same. The inability to distinguish between the radiogenic ages of these materials becomes especially clear when one compares the results of the geologically oldest sample, the Valley Spring gneiss (53gn), and the second youngest the Sixmile granite (20gr). Likewise, no significant differences exist between the various ages obtained on the rocks of the Lone Grove pluton.

A thorough investigation of the Petrick quarry granite involving the analyses of nine mineral phases was performed. A detailed discussion of this sample will be given as representative of the behavior of the various minerals within one locality. Following this, the individual mineral systems from all the sample localities will be treated in order. In this manner the capabilities and limitations of each particular geochronological system can be evaluated.

Petrick Quarry Granite:

The geochronological data for the Petrick quarry granite (3gr) are given in Tables 2 and 3 and Plate II. This rock is typical of the coarse-grained, grayish-pink, porphyritic Town Mountain granite from the Lone Grove pluton. It appears to be of definite magmatic origin and chemically lies close to the ternary minimum in petrogeny's residua system. Microcline, quartz, and oligoclase form the bulk of the rock while biotite and hornblende make up the several percent of mafic constituents. Accessory minerals include opaques, zircon, allanite, apatite, fluorite, and sphene, all of which appear to be primary components of the rock. A small amount of sericite in the feldspars is the only secondary mineral present.

The microcline occurs both in the groundmass and the phenocrysts. It displays a typical perthitic texture with exsolution albite lamellae making up approximately 20% of the grain. Rapakivi and antirapakivi textures with oligoclase are common,

especially in the larger grains. The quartz occurs in anhedral, irregular grains which are clear to slightly bubbly. The oligoclase forms anhedral grains which usually have well-developed albite twinning and a slight zonal structure. The biotite is greenish-brown in color and occurs as flakes or in aggregates along with the hornblende. The hornblende is pleochroic light yellowish-green to dark green and occurs as subhedral prismatic crystals locally replaced by biotite. The grain-size of the groundmass averages 6-8 mm and the phenocrysts range up to 36 mm in length. Chemical analysis of the biotite and hornblende from the Petrick quarry granite are included in Table 4.

The methods employed in the mineral separations are described in the Experimental Procedure. Modal analyses for those mineral separates which were used directly to obtain ages are given in Table 7. The feldspars were separated from the -35+80 mesh fraction by heavy liquid floatation in tetrabromoethane. At a density of 2.58 all of the mineral components except microcline sank in the liquid. The density was so adjusted that only the lightest fraction of the potassium feldspar was retained in order to minimize the amount of included exsolution albite. The oligoclase separate was obtained by retaining only that density fraction lying between 2.63 and 2.64. After repeated recycling through these liquids a separate essentially free of microcline and containing less than 1% quartz was obtained. It was extremely difficult to distinguish between the primary oligoclase

Table 4. Chemical and partial chemical analyses of some minerals from the Lone Grove pluton. Analyzed at the California Institute of Technology Silicate Analysis Laboratory. Analyst: A. D. Maynes.

	3gr biotite	3gr hornblende	3p-2 biotite	41gr biotite	4gr biotite
SiO_2	34.75	38.45	34.26		
TiO_2	3.53	2.97	3.01	2.58	2.88
Al_2O_3	12.95	9.36	13.06		
Fe_2O_3	4.10	6.44	7.02	6.58	4.48
FeO	28.65	24.71	26.61	24.60	22.91
MnO	0.35	0.60	0.80	0.35	0.53
CaO	0.49	10.48	0.00		
MgO	2.98	2.12	2.07	5.71	5.60
Na_2O	0.11	1.56	0.10		
K_2O	8.67	1.41	8.42		
H_2O+	2.45	1.20	2.82		
H_2O-	0.12	0.11	0.24		
P_2O_5	0.24	0.17	0.03		
Total	99.39	99.58	98.44		
Density	3.21	3.37	3.23		
N_x	1.610	1.695	1.611		
N_y	1.664	1.714	1.666		
N_z	1.664	1.720	1.666		
2V	small (-)	55° (-)	small (-)		
Z	--	22°	--		
Pleochroism	light yellowish-brown to dark brown	yellowish-green to olive green to dark green	light yellowish-brown to dark brown		

and secondary albite; however, oil emersion determinations suggest that less than 2% of this separate is albite.

Biotite and hornblende were also separated from the -35+80 mesh fraction. The Frantz magnetic separator was used first to remove the mafic minerals from the other constituents, and then to separate the biotite and hornblende from each other. Due to similarities in magnetic properties, this latter separation was accomplished only with difficulty and the final separates still contained appreciable quantities of the other mineral. A second biotite separate was made from the -80+115 mesh fraction in order to investigate the possibility of argon loss from finer material. This material was passed through heavy liquid diiodomethane in addition to the Frantz and a much purer separate was obtained.

All of the minerals--oligoclase, albite, hornblende, apatite, fluorite, and allanite--used for making common strontium isotopic analyses were obtained with special care to eliminate contaminants. In addition to heavy liquids and the Frantz magnetic separator, the Wilfley table and hand picking techniques were used. The exsolution albite was obtained by hand picking perthite grains and crushing them to -100+200 mesh in order to free the albite. Heavy liquids were then used to separate the two feldspar phases; oil emersion determinations showed the final separate to consist of a plagioclase of composition Ab_{92-94} with less than 5% of microcline or oligoclase. The heavy minerals

were first concentrated on the Wilfley table and then separated according to magnetic and density properties. The fluorite and apatite were separated chemically due to the rapid solubility of apatite in HNO_3. In the case of hornblende approximately 2% poikilitic biotite intergrowths remained in the final material.

Rb^{87}-Sr^{87} ages were obtained on microcline, biotite, and total rock, and K^{40}-Ar^{40} ages were obtained on microcline, oligoclase, biotite, and hornblende. The enrichment in Sr^{87} is about 85% for the biotite, 11% for the microcline, and 8% for the total rock. The Rb^{87}-Sr^{87} ages from both the strontium spiked runs and the strontium composition runs are given for the microcline and total rock in Table 2. However, since the age determined by the latter method is more precise, it will be used throughout the discussion. Except for the oligoclase, the minerals yielded argon which was 98% or more radiogenic.

With the exception of the K^{40}-Ar^{40} ages on the feldspar, all of the minerals yield ages lying between 1000 and 1050 million years. The experimental error assigned to each age determination has been discussed previously and is believed to be a true indication of the precision. In the cases of the five repeat Rb^{87}-Sr^{87} and K^{40}-Ar^{40} biotite analyses, the obtained reproducibility is approximately equal to that estimated. Although the biotite and hornblende K^{40}-Ar^{40} ages are somewhat higher than the biotite and microcline Rb^{87}-Sr^{87} ages, a meaningful comparison between the two dating methods is difficult to make in light of the uncertainties

in the decay constants.* The microcline and oligoclase K^{40}-Ar^{40} ages are 975 and 945 million years, respectively. The low microcline age is in line with the findings of most other workers with potassium feldspars from intrusive rocks, who attribute this effect to argon loss by diffusion. The similar low age on the oligoclase indicates that this plagioclase has also suffered some loss of argon.

In addition to the individual mineral ages, a total rock Rb^{87}-Sr^{87} age was also determined on the Petrick quarry granite. The importance of the total rock age lies in the fact that only the rock as a whole must remain a closed system in respect to rubidium and strontium in order to yield a valid age. This is opposed to individual mineral ages where the mineral phase itself must have remained closed. Thus, if at some time subsequent to the formation of the rock local rubidium or strontium movement has occurred in the rock, a representative total rock sample will still yield the original age. It is, of course, necessary to take a sample of adequate size so that local enrichments of daughter or parent are not selectively taken. A mineralogically homogeneous rock should be sampled over a volume large compared to the individual grain-size. In this way, the sample will contain the mineral phases in the same proportion as they occur in the rock. In the case of heterogeneous material, such as banded gneiss, where long distance element movement may have occurred, it is necessary to

* Despite several exceptions, this tendency for K^{40}-Ar^{40} ages to exceed Rb^{87}-Sr^{87} ages by 2-4% on presumably good dating minerals is characteristic of all of the sample localities where such a comparison can be made. Possible interpretations of this effect will be given in the Conclusion.

acquire a sample large enough to include all lithological units in their natural proportions. It is possible even in a homogeneous rock, such as the Petrick quarry granite, that movement of minor elements may occur over large distances; however, it was here assumed that a block of material representative of the gross mineralogy would also be representative of the rubidium and strontium contents.

The total rock sample for the Petrick quarry granite was split from the same material used to obtain the mineral separates prior to any sizing or processing other than initial crushing. From an original 50 pounds (approximately an 8'' cube) of rock, 5 pounds were reduced to -80 mesh and a split for the chemical analysis was taken from this material.

The observed Rb^{87}-Sr^{87} total rock age on the granite was 1000 ± 40 million years, which is within experimental error with the Rb^{87}-Sr^{87} ages of the biotite and microcline. It therefore appears that in this rock the individual minerals did remain closed systems, and, thus, the total rock merely reflects the age of the constituent phases.

Since individual analyses had been made of all those minerals expected to contribute significantly to the rubidium and strontium contents of the total rock, it was possible to calculate the rubidium and strontium composition and age using these analyses and the rock mode (see Table 5). The calculated age was 1030 million years, or 30 million years greater than the observed

Table 5. Comparison of observed and calculated rubidium and strontium concentrations and total rock ages. Calculated values were arrived at from individual mineral analyses and rock modes (converted to weight percent).

	Rb, ppm		Sr, ppm		Sr^{87*}, ppm		Age, my	
Rock	obs.	calc.	obs.	calc.	obs.	calc.	obs.	calc.
3gr	159	154	113	111	0.67	0.67	1000	1030
22Igr	285	281	80	84	1.15	1.11	960	940

one. It is doubtful that this age difference, which lies within the expected experimental error, is real. In order for it to be real, either a strontium having a Sr^{87}/Sr^{88} ratio less than that of normal isotopic composition or an excess of rubidium unaccompanied by radiogenic Sr^{87} would be required from some unanalyzed phase of the rock. This comparison is believed to further indicate that the experimental uncertainty assigned to the analyses is not too liberal and gives a true indication of precision.

In particular, the total rock granite shows no indication of having a significantly older age than that of the constituent minerals. If, of course, some radiogenic strontium were formed prior to the crystallization of the rock, it would probably have been homogenized with the common strontium of the magma, and, therefore, tend to increase the Sr^{87}/Sr^{88} ratio of the original strontium incorporated into the minerals at their time of formation. A discussion of the primordial Sr^{87}/Sr^{88} ratio and the length of time a system can exist until it evolves its observed common strontium isotopic composition is given by Compston, Jeffery, and Riley (1960). As an extreme case, we may assume the magma originally had access to a primordial strontium with an isotopic composition of $Sr^{87}/Sr^{88} = 0.0833$ (Gast, 1960 and 1955; minimum value for achondrites, normalized to make $Sr^{86}/Sr^{88} = 0.1194$). Under this condition, the maximum length of time the Town Mountain granite could have existed with its present Rb/Sr ratio is 1175 million years, or 150 million years

longer than the mineral ages. A more reasonable estimate of the initial strontium isotopic composition would give a maximum age of 1100 million years.

In addition to those minerals on which direct age measurements were made, several other minerals were investigated to determine their potassium, rubidium, and strontium contents and strontium isotopic composition. Several minerals having low Rb/Sr ratios were used to determine the isotopic composition of the strontium incorporated into those minerals at the time of crystallization. Oligoclase, exsolution albite, hornblende, apatite, fluorite, and allanite were analyzed and found to have similar initial Sr^{87}/Sr^{88} ratios of 0.0843 ± 0.0002 after correcting for the small contribution from rubidium decay. The potassium, rubidium, and strontium contents of the quartz were near the blank levels. The potassium content is approximately 8 ppm while the rubidium and strontium contents are less than 0.05 and 0.2 ppm, respectively (see Table 8). The quartz was leached in HF for 20 minutes prior to analysis in order to remove any feldspar from the separate.

Individual Mineral Ages:

The following section will be based on the behavior of the various mineral systems rather than sample localities. Because of the concordance of the ages from most of the different localities, such a treatment is more coherent than a comparison of the individual geochronological systems within each rock.

In those cases where anomalous ages require special comment, the discrepancies will be discussed in the subsequent section on anomalous ages. The weathering study will also be presented in a separate section.

Microcline: Fifteen microclines (3gr, 3p-1, 3p-3, 3p-4, 50gr, 41gr, 128gr, 22Igr, 22IIgr, 4gr, 6gr, 20gr, 53gn, 14rp-1, and 14rp-2) from fresh rock from both the Lone Grove pluton and other units of the area have been investigated. These samples include microclines from granites, pegmatites, rhyolite porphyry, and a gneiss. The feldspars appear to be quite fresh although some cloudy patches which often contain sericite are present in most of them. This phenomenon is present in many feldspars and often appears to be unrelated to rock weathering. It is quite possible that some late stage deuteric alteration of the rock produces this cloudy appearance. Microclines from the Town Mountain granite and the rhyolite porphyry frequently show a rapakivi texture with the plagioclase. Perthitic textures are commonly developed in all the microclines, and exsolution albite occurs in amounts ranging from barely perceptible to over 30% of the grain. An attempt has been made to remove the albite from the potassium feldspar in the granites and gneiss, and the estimated modes of the final separates are given in Table 7. A more detailed petrographic description of the microclines from each sample is given in the Appendix.

A uniform age pattern, in which the ages lie between 980 and 1065 million years, was obtained on all the microclines except those from the rhyolite porphyry by the Rb^{87}-Sr^{87} method. Although the microcline is invariably the least radiogenic mineral in any of the suites of minerals dated by this method, careful analyses have yielded ages which consistently fall within this rather narrow time interval. This range is just slightly greater than the estimated experimental uncertainty, and it is difficult to say if the 8% age spread is due to real variations or analytical errors.

If one excluded the microcline (53gn) with the 1065 million year age, which is the only feldspar from a metamorphic rock, all of the remaining ages would lie within experimental error of each other. Some retention of radiogenic strontium from an earlier history could explain the slightly higher age in the microcline from the Valley Spring gneiss; however, the age dispersion between these feldspars is too small to conclusively demonstrate such an effect. A more precise method of mass spectrometric analysis must be perfected before it is possible to demonstrate whether or not these differences of several percent in the Rb^{87}-Sr^{87} ages are real.

K^{40}-Ar^{40} determinations were also made on five of the microclines (3gr, 3p-1, 50gr, 4gr, and 53gn). These ages were all 5-15% lower than the corresponding Rb^{87}-Sr^{87} ages or the K^{40}-Ar^{40} ages on cogenetic biotites and hornblendes. They

ranged from 985 million years for the microcline from the gneiss (53gn) to 915 million years for the microcline from the medium-grained granite (4gr) of the Lone Grove pluton. The discrepancy in K^{40}-Ar^{40} ages on microclines is similar to the findings of numerous other workers, who attribute this low age to argon leakage from the mineral (Wetherill, Aldrich, and Davis, 1955; Wasserburg, Hayden, and Jensen, 1956; Goldich, Baadsgaard, and Nier, 1957). The relatively high retentivity of argon in the Llano microclines is greater than that found in numerous other localities where commonly 30% of the argon has escaped. It is interesting to note that the microcline (4gr) most nearly having a stoichiometric potassium content and displaying the least evidence of crystal disruption by exsolution lamellae has lost the greatest amount of argon.

One case of apparently concordant K^{40}-Ar^{40} ages on microcline and biotite occurs in a pegmatite (3p-1) from the Petrick quarry. However, as discussed later, this biotite has not completely retained either its radiogenic argon or strontium. It is of interest that in such a case where coexisting biotite has suffered daughter loss, the microcline has not lost any more argon than under undisturbed conditions.

Samples of microcline phenocrysts from two separate localities (14rp-1 and 14rp-2) within the llanite dike system gave Rb^{87}-Sr^{87} ages which were considerably lower than those of the other feldspars. The ages of 935 and 890 million years are

approximately 100 million years lower than any of the other Rb^{87}-Sr^{87} microcline ages and well outside of experimental error with them. They are believed to reflect a real younger age for the rhyolite porphyry. This is compatible with the geologic evidence which shows the llanite dikes to represent the youngest intrusive event in the area. If these ages do mean a time of emplacement for the llanite of about 910 million years, it is possible that such a later igneous activity might have had a pervasive effect on the older rocks of the area. However, the limited extent of occurrence of these dikes suggests that it is unlikely that a regional effect accompanied them. A narrow chill zone at the contact of the dikes also indicates that the surrounding wall rock was cooler than the intrusive. No other geochronologic data show a definite relationship to this later event; however, the possibility cannot be ruled out that a few percent age scattering may be the result of minor, later heating.

Plagioclase: Two plagioclases were analyzed for their potassium and argon contents. They include oligoclase (3gr) from the Petrick quarry granite and sodic oligoclase (3p-4) from a pegmatite in the Petrick quarry. The former material has already been discussed under the heading of Petrick quarry granite. It occurs in subhedral, albite-twinned grains as a primary constituent of the granite. The latter sodic oligoclase comes from a basic microcline-quartz-biotite-hornblende-

plagioclase pegmatite. The plagioclase shows well-developed albite twinning and occurs as subhedral to euhedral crystals up to 1" in size. Numerous poikilitic inclusions of biotite, microcline, and quartz are found in the oligoclase. The hornblende and plagioclase appear to be a coarsening in grain-size of the adjacent aplite which surrounds the pegmatite. No intergrowths of potassium feldspar were observed in either of the plagioclase mineral separates.

The K^{40}-Ar^{40} ages on these two plagioclases are 945 and 855 million years, respectively. This is 10 to 20% below the presumed age of the rock, and suggests that low K^{40}-Ar^{40} ages might be expected in plagioclases as well as potassium feldspars. Argon loss by diffusion would be the most probable cause of such an effect.

McDougall (1961), however, gives evidence for the rather complete argon retention in plagioclases (Ab_{40}) from a Mesozoic dolerite. He concludes from the narrow spread in ages obtained on cogenetic plagioclase and pyroxene that little argon loss has occurred from these minerals. Geologic evidence suggests that the ages could not be more than 15% too low. If the uniform ages obtained on the dolerite do correctly date the time of intrusion, several explanations of this discrepant plagioclase behavior are possible. Differing chemical or thermal histories may have significantly changed the ability of the mineral to retain argon. It is also possible that young plagioclases suffer

less loss of their radiogenic argon than older ones.

Muscovite: Because of the paucity of muscovite-bearing rocks in the Llano Uplift, only three muscovites were analyzed in this study. They include a muscovite from the two-mica Sixmile granite (20gr), a pegmatitic muscovite from a dike in the Valley Spring gneiss (21p), and a secondary sericitic mica from the medium-grained granite of the Lone Grove pluton (4gr). The muscovite from the Sixmile granite appears to be a primary constituent of the rock. It occurs as irregular flakes up to 2 mm in size and makes up approximately 0.6% of the granite. The pegmatitic muscovite occurs in a quartz-microcline-muscovite pegmatite dike which appears to be approximately syngenetic with the surrounding Valley Spring gneiss. This mica forms subhedral crystals and booklets up to 1" in diameter. The sericitic mica from the medium-grained granite appears to be of deuteric origin and replaces both the feldspars and the biotite. Some coarser grains of white mica may also be primary muscovite; however, most of it is secondary in origin. In addition, chlorite and magnetite replacing biotite and a small amount of carbonate are also present as deuteric minerals.

All of the muscovites yield both K^{40}-Ar^{40} and Rb^{87}-Sr^{87} ages which lie within the 1020 to 1080 million year interval. The two primary micas (20gr and 21p) have K^{40}-Ar^{40} ages which are about 4% higher than their Rb^{87}-Sr^{87} ages. This relative discordance is similar to that found with most of the other minerals.

The K^{40}-Ar^{40} radioactive system gives ages of 1080 and 1075 million years and the Rb^{87}-Sr^{87} radioactive system gives ages of 1035 and 1040 million years, respectively, on these two samples. On the other hand, the secondary sericite from the medium-grained granite (4gr) gives a K^{40}-Ar^{40} age of 1020 million years and a Rb^{87}-Sr^{87} age of 1075 million years. In this case the age by the former method is 5% lower than that of the latter. This reversal in ages between the two decay systems is well outside of experimental error. The Rb^{87}-Sr^{87} age of 1075 million years on the sericite is the oldest age obtained by this method, despite its occurrence as a secondary mineral. If the age correctly represents the time of deuteric alteration of this rock, all of the other Rb^{87}-Sr^{87} ages from the Lone Grove pluton would have to be at least several percent too young.

In addition to the obvious possibility of daughter or parent loss or gain due to some thermal or chemical process, another possible explanation of this anomaly presents itself. If the secondary mica incorporated a strontium already enriched in radiogenic Sr^{87} into its original structure at the time of formation, it will yield a Rb^{87}-Sr^{87} age which will be greater than the true age if the normal value for the Sr^{87}/Sr^{88} ratio of the included strontium is used in the calculation of the radiogenic strontium. An enrichment of about 10% in the Sr^{87} of the original strontium would be necessary to account for the relative discrepancy between the Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages in the sericite.

If the primary minerals in this rock existed for an appreciable length of time prior to deuteric alteration, they would, of course, be increasing their Sr^{87}/Sr^{88} ratio by radioactive decay. Since the K^{40}-Ar^{40} age of the sericite suggests that the time of secondary mica formation was not more than 50 million years after the time of formation of the rock, or, more specifically, the absolute age of the primary minerals, only a strontium derived mainly from the biotite could have attained such an isotopic composition after this time interval.

If the secondary chlorite also present as a deuteric mineral in this rock had drawn its original strontium from the same source as the sericite, an anomalously high Sr^{87}/Sr^{88} ratio should be detectable. This is possible because the chlorite has a low enough Rb/Sr ratio to allow a rather accurate correction to original composition to be applied. The rubidium and strontium contents and the calculated composition of the strontium initially incorporated into the chlorite are given in Table 6. Since this mineral does not show an enrichment in its original strontium, it must be concluded that either the sericite received its strontium from another source or at an earlier time or else no effect from an anomalous original strontium is to be expected. Petrographically, the chlorite shows a closer relationship with the biotite than does the sericite; however, the time sequence of the alteration is not clear.

Hornblende: Four granitic hornblendes (3gr, 50gr, 41gr, and 128gr), one pegmatitic hornblende (3p-4), and one hornblende from an amphibolite in the Packsaddle formation (25am) were analyzed for their potassium and radiogenic argon contents. The granitic hornblendes occur along with biotite as the mafic constituents of the Town Mountain granite from the Lone Grove pluton. They are pleochroic light yellowish-green to dark green and occur as subhedral, prismatic crystals up to 8 mm in length. Inclusions of apatite, opaques, and zircon, as well as poikilitic intergrowth with biotite, are commonly observed. Although some replacement of the hornblende by biotite has occurred, the remaining grains are quite fresh and unaltered. The pegmatitic hornblende forms well-developed prismatic crystals in excess of 1" in length. It occurs along with plagioclase in a basic pegmatite dike in the Petrick quarry and shows a genetic relationship with surrounding aplite. Both the granitic and the pegmatitic hornblendes are highly potassic and contain 1.1 to 1.3% K. The hornblende from the amphibolite is pleochroic light yellowish-brown to green to dark brownish-green and occurs in elongate, prismatic grains ranging from 0.05 to 3 mm in length. The amphibolite is dark bluish gray and contains quartz and andesine in addition to the hornblende as major components. A weakly developed foliation and a strong lineation characterize the rock, which may have originally been a basaltic lava.

The resultant ages range from 980 to 1080 million years

and are in good agreement with the other geochronologic systems included in this study. With the exception of one sample (50gr), all of the other ages lie within a 1035 to 1080 million year interval. These findings are compatible with those of Hart (1961) and attest to this mineral's ability to quantitatively retain argon. The experimental error assigned to these ages suggests that a real spread of several percent does exist between them. Slightly varying thermal or chemical histories or the incorporation of original radiogenic argon into the crystal lattices may have produced this spread in ages. It is also possible that analytical difficulties encountered from sample inhomogeneity is partially responsible for this spread. The effect of biotite impurity in the hornblende separates can be quite serious because of the relatively high potassium content of the mica. Repeat analyses have yielded variations of over 2% in the potassium concentration of the Petrick quarry granitic hornblende (3gr).

Rubidium^{87}-strontium^{87} ages were not obtainable on the hornblendes due to unfavorable Rb/Sr ratios.

Biotite: A large number of biotites have been investigated. Their ages fall into four categories, which include (1) concordant Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages on biotites from fresh granites and gneiss; (2) somewhat low Rb^{87}-Sr^{87} but good K^{40}-Ar^{40} ages on biotites from obviously weathered granites; (3) anomalously low Rb^{87}-Sr^{87} and to a lesser degree K^{40}-Ar^{40} ages on a suite of pegmatitic biotites from the Petrick quarry (3p); and (4) anoma-

lously low Rb^{87}-Sr^{87} but good K^{40}-Ar^{40} ages on biotites from a foliated granite (22gr). Only the first category involving concordant ages will be included in this section. The results of the weathering study and the anomalous samples will be discussed subsequently.

Eight biotites obtained from granites from the Lone Grove pluton (3gr, 50gr, 41gr, 128gr, and 4gr), Oatman granite (6gr), Sixmile granite (20gr), and Valley Spring gneiss (53gn) were dated by both the Rb^{87}-Sr^{87} and the K^{40}-Ar^{40} methods. The petrographic relationships of the individual biotites are discussed in the Appendix; in all cases they occur as primary constituents of the granites and gneiss. The biotites are usually pleochroic light brown to dark brown, and occur either with hornblende or alone as the mafic constituent(s) of the rock. Chlorite is usually present in very minor amounts except in the medium-grained granite (4gr) where it occurs almost in equal abundance with the biotite. A chemical analysis of the biotite from the Petrick quarry (3gr) and partial analyses of two other biotites from the Lone Grove pluton (41gr and 4gr) are given in Table 4. In general, the biotites appear to have high Fe^{++}/Mg^{++} ratios and contain several percent titanium. All of the host rocks appeared quite fresh and unweathered in hand specimen and thin section with the possible exception of the Golden Beach granite (41gr), which

shows some loss of strength and rigidity* as compared with similar material from greater depths in quarries.

The Rb^{87}-Sr^{87} ages range from 975 to 1025 million years and the K^{40}-Ar^{40} ages range from 1025 to 1075 million years. Spreads of only 50 million years in the ages of these biotites by each of the two methods are just outside of experimental error and are considered to be in good agreement. The mechanism responsible for the 5% spread in ages is not well understood. In the case of the Rb^{87}-Sr^{87} ages, a significantly smaller range is obtained if we omit the biotite with the 975 million year age from the somewhat suspect Golden Beach granite. As will be further supported by the weathering study, it is possible that incipient surface alteration has produced its lower age. The lowest K^{40}-Ar^{40} biotite age also occurs in this granite; however, the effect of weathering on this decay system is less clear.

K^{40}-Ar^{40} analyses were made on two different mesh sizes of biotite from the Petrick quarry granite (3gr) in order to see if any loss of argon had occurred in the finer fraction. Material of -35+80 and -80+115 mesh size yielded identical ages.

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* One of the best criteria for determining the freshness of a rock was found to be its elasticity when struck by a sledge hammer. A sharp, ringing rebound is encountered when fresh material, such as recently exposed granite from a quarry, is struck, while a dull thud is produced on weathered material. Rocks which appear completely unaltered under the petrographic microscope give their first clue of incipient weathering in this manner.

Anomalous Ages:

Two cases of anomalous biotite ages were encountered from rocks which gave no field or petrographic evidence of alteration. These included a suite of pegmatitic biotites from the Petrick quarry (3p) and biotites from the two portions of the foliated granite (22gr). In order to investigate these anomalies, a rather thorough analysis was made of these rocks to see if any clues to the biotite's behavior could be found in the coexisting minerals. The following discussion will include those accompanying experiments which shed light on this problem.

Anomalously low ages were obtained on the biotites in several pegmatites from the Petrick quarry (3p). Four separate biotite suites were analyzed and the resultant ages are included in Tables 2 and 3 and Plate II. These biotites occur in large crystals up to 10'' in diameter along with microcline and quartz in large pegmatite dikes which cut the enclosing granite. In addition, one of the pegmatites (3p-4) also contains plagioclase and hornblende crystals 1'' or more in length. Accessory gadolinite and fluorite occur rarely in some of the pegmatites. The pegmatites are often surrounded by fine- to medium-grained aplite, which separates them from the granite. The biotite is quite fresh and shows no evidence of alteration or mechanical strain.

It is apparent that these micas have all suffered losses

both in their Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages. The Rb^{87}-Sr^{87} ages range from 955 million years for the biotite from the basic pegmatite (3p-4) to 655 million years in the most discrepant case (3p-3). Each of the biotites also have somewhat low K^{40}-Ar^{40} ages, although this effect is only 5-10% in all cases except one (3p-3), where an age of 805 million years is found. Cogenetic microclines from the pegmatites yield normal Rb^{87}-Sr^{87} ages and a hornblende from the basic pegmatite (3p-4) also gives a normal K^{40}-Ar^{40} age. In addition, a microcline from one of the pegmatites (3p-1) shows no greater loss of argon than is encountered in the other rocks. A total rock Rb^{87}-Sr^{87} age on the aplite (3ap) adjacent to one of the pegmatites gives an age of 1010 million years.

The differences in the amount of rubidium and the resultant radiogenic strontium between the duplicate runs on separate splits of the first biotite (3p-1) point out the extreme variations in trace element content of pegmatitic minerals. These two analyses along with that of a biotite completely enclosed in massive quartz (3p-2) from the same pegmatite dike all give similar Rb^{87}-Sr^{87} ages despite their spatial separation and variable rubidium contents. This suggests that within this one pegmatite dike, the phenomenon responsible for the low ages has affected all the biotites to the same extent.

Coarsely crystalline fluorite occurred adjacent to the biotite with the lowest ages (3p-3). An analysis of the strontium

isotopic composition from this fluorite showed it to be enriched in Sr^{87} by approximately 3% relative to other common strontium minerals from the granite and pegmatite (see Table 6). A careful study of the fluorite showed it to be coated by a thin, brownish-yellow incrustation. It was therefore decided to perform a leaching experiment in order to see if the anomalous strontium was contained by the secondary material or was actually a part of the fluorite lattice. The fluorite was leached in 0.5N HNO_3 for 30 minutes, and the incrustation was readily dissolved with the evolution of a gas, possibly CO_2 from a carbonate. This soluble material represented approximately 2% of the total fluorite and was found to be 5% enriched in Sr^{87}. The residue, which appeared to be only clear cleavage fragments of fluorite, was also analyzed and found to contain a normal strontium isotopic composition. It is therefore most probable that the strontium occurs in two discrete sites--one containing strontium of normal isotopic composition incorporated into the original mineral, and a second containing strontium enriched in Sr^{87} which may be selectively removed by acid leaching. A material balance between the initial analysis on the total fluorite and the second series of experiments on the leachable and residual fractions is somewhat discrepant. However, original inhomogeneities in the amount of incrustation or selective enrichment of this more brittle material in the composite sample are likely explanations of this effect.

These results indicate that a strontium somewhat enriched in Sr^{87} has been transferred to the surface of the fluorite. Since the surrounding granite has a strontium enrichment of about 8%, it is not possible to say whether the strontium from the incrustation was derived from the pegmatitic biotite with a considerable dilution by normal strontium or from the surrounding granite with little normal dilution. However, this experiment does attest to the mobility of radiogenic strontium from its original site of production to the surface of the fluorite.

It was also decided to analyze the strontium isotopic composition of the sodic oligoclase from the basic pegmatite (3p-4). In contrast to the fluorite, this mineral yielded a normal Sr^{87}/Sr^{88} ratio. Since the plagioclase contains almost ten times more strontium, however, an effect quantitatively equal to the one encountered in the fluorite would not be seen.

It is difficult to postulate a mechanism responsible for these low Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages in the pegmatitic biotites while the adjacent granitic biotite has not suffered a similar effect. A careful petrographic study of these materials has yielded no definite clue in this regard. Chemical analyses on pegmatitic and granitic biotites from the Petrick quarry show no significant differences which might cause the one to be more susceptible to age loss (see Table 4). The age of 655 million years on the one biotite sets a maximum time limit on the occurrence of the phenomenon responsible for the age loss. Even if some continuous

mechanism during the early history of the rock is responsible, it would have to be operative up to this time. On the other hand, no minimum limit on the time of age failure is imposed, and the present-day circulation of meteoric water through the rather open pegmatitic structure may be responsible. The fact that Goldich (1960) was able to obtain concordant ages on pegmatitic biotite from this same locality on material collected during the period of active quarrying in 1940 lends some credence to this hypothesis. The Petrick quarry samples used in this investigation have been exposed for some twenty years following the discontinuation of quarrying operations. However, the effect of such a short time interval will have to be studied more closely before it can be seriously proposed.

A second incident of discrepant biotite ages was encountered in the foliated granite (22gr) from Lone Grove. This coarse-grained, distinctly foliated granite is texturally and mineralogically somewhat different from the other rocks of the Lone Grove pluton. Microcline, oligoclase, quartz, and biotite make up the bulk of the rock, while opaques, sphene, zircon, allanite, and apatite occur in accessory amounts. This rock is the only coarse-grained granite from the Lone Grove pluton which does not contain hornblende. The average grain-size is 2-4 mm; however, microcline phenocrysts up to 30 mm in length occur throughout the rock. A well-developed orientation of the mica and feldspar gives the rock its foliation. Although this texture appears to be related to

primary flowage, a few broken feldspar and quartz grains suggest that some cataclastic deformation may also have occurred. The contact between this granite and the adjacent Town Mountain granite is not exposed; however, the rocks appear to be genetically related. A prominent late Paleozoic (?) fault lies just to the west of this foliated granite.

A fresh block of this granite was divided into two fractions each measuring 6" x 10" x 8". These fractions were then treated as independent samples in order to see if short range variations in the behavior of the geochronological systems occurred. The total rock sample of this granite represents a split taken from one of these fractions (22Igr).

The biotites from this granite give K^{40}-Ar^{40} ages which are concordant with the other granitic micas; however, they yield anomalously low Rb^{87}-Sr^{87} ages of 730 and 665 million years. Rb^{87}-Sr^{87} ages on the microclines from this granite are consistent with those encountered in the other granitic microclines and show no evidence of an age loss. Although a minor cataclastic texture is apparent in thin section, the biotite shows no textural evidence of recrystallization or alteration. The fresh appearance of the rock also discounts an extensive weathering effect. As in the case of the anomalous pegmatite biotites, the phenomenon responsible for the low age must have been operative within approximately the last 650 million years; however, no minimum age can be assigned to it.

The low Rb^{87}-Sr^{87} age of the biotites could be due either to the loss of radiogenic strontium or the addition of rubidium. The facts that (1) the Rb^{87}-Sr^{87} age difference between the two fractions of the granite is mainly due to a variation in rubidium content, and (2) evidence related to the Rb/K partitioning factor between the biotite and microcline, which will be discussed subsequently, suggest that an addition of rubidium to the biotite could be at least partially responsible for the low age.

It was decided to look at several common strontium minerals from the foliate granite in order to see if any anomalous strontium was present in them. Apatite, allanite, and oligoclase from 22Igr were analyzed and the results are presented in Table 6. Upon correcting for rubidium decay, the first two minerals were found to have entirely normal strontium isotopic compositions while a 0.5% enrichment in Sr^{87} was observed in the plagioclase. A stripping of the oligoclase in which approximately 5% of the feldspar was dissolved in 10% HF failed to reveal a more enriched, and presumably surfacial, strontium fraction. In addition, a leaching experiment on the total rock (22Igr), in which the powdered material was agitated for 10 hours in 0.02 N HCl, failed to remove any appreciable amount of soluble radiogenic strontium.

A total rock Rb^{87}-Sr^{87} analysis was also made on the granite (22Igr). Since individual analyses were available for those minerals which would contribute significantly to the rubidium and strontium contents of the rock, it was possible by using the

rock mode to calculate a total rock composition and age and compare them with the experimental ones. If the low biotite age is due to radiogenic strontium loss, such a comparison would allow one to determine whether radiogenic strontium not accounted for in the individual mineral analyses was present in the total rock. If such strontium were present either in some unanalyzed mineral or as an interstitial phase, the experimental age would be greater than the calculated age of 940 million years (see Table 5). The total rock determination yielded an age of 960 ± 25 million years, which suggests that the greater part of the radiogenic strontium which may have left the biotite has also been removed from the rock as a whole.

The 0.5% enrichment in Sr^{87} occurring in the oligoclase attests to some movement of radiogenic strontium within this rock. It is not possible, however, to definitely correlate the low biotite age with this slightly anomalous feldspar strontium. Strontium with the isotopic composition found in the plagioclase would have been generated by the total rock 30 million years after its formation, and, therefore, a late stage magmatic process may have redistributed the strontium at that time. The biotite must have undergone its loss of age within the last 700 million years. On the other hand, it is equally possible that the plagioclase has gained a small amount of the radiogenic strontium loss by the biotite.

If the rubidium or strontium simply moved within the rock as a closed system, it would mean that the true age of the rock is 960 million years and the biotite has gained rubidium or lost strontium while the microcline has done the opposite. The fact that most of the other minerals of the rock have not participated in such a strontium exchange makes this hypothesis doubtful, at least for strontium movement. The biotite K^{40}-Ar^{40} ages of 1040 and 1050 million years also makes such a hypothesis extremely improbable.

It is difficult to postulate a mechanism which disturbed the Rb^{87}-Sr^{87} age of the biotite without affecting its K^{40}-Ar^{40} age or any of the other mineral ages of the rock. The incorporation of some radiogenic Sr^{87} into the plagioclase also appears to have occurred; however, it is not established that the time of strontium introduction into the feldspar is that of the biotite age loss. An appeal to ordinary surficial weathering is difficult to support in the light of the results obtained on obviously weathered biotites (128Wgr and 149gr), where a much smaller effect was observed on more altered material. The possibility that a circulation of hydrothermal or meteoric water through the rock has disrupted the mica age cannot be discounted. The proximity of a prominent Paleozoic fault zone just west of this granite could be considered evidence for a channel permitting such fluid migration.

However, without further investigation it is not possible to demonstrate conclusively a causal relationship between this fracture zone and the low Rb^{87}-Sr^{87} age. The appreciable difference in rubidium content between the two adjacent fractions of the granite suggest that short range processes of element distribution were operative either in the initial mineral crystallization or the later age disruption.

A number of leaching experiments were performed on biotite separates from (1) Petrick quarry granitic biotite (3gr), (2) Petrick quarry pegmatitic biotite (3p-2), and (3) biotite from the Lone Grove foliated granite (22Igr). The first mica represents material yielding concordant ages, while the latter two have low Rb^{87}-Sr^{87} ages. The purpose of the experiment was to see if any special behavior might distinguish the concordant biotites from those which had suffered some loss of daughter or gain in parent. The biotite was agitated for 20 hours in 0.1 N HCl and the solution was then analyzed for rubidium and strontium. Under this treatment all material lost from 1 to 3% of its rubidium and radiogenic strontium with no apparent distinction between the samples. It was noted, however, that all of the samples preferentially lost radiogenic strontium to rubidium so that the leachable fraction gives apparent ages higher than the total biotite by 20 to 40%. In addition, the biotites lost 15 to 25% of their normal isotopic composition strontium, a fact probably attributable to the preferential solution of apatite and other impurities in the mineral separate.

Weathering Study:

In addition to the analyses on fresh rocks, it was decided to investigate the effects of weathering on the various geochronological systems. Therefore, two samples of obviously altered Town Mountain granite from the Lone Grove pluton were also included in the study. They represent granites from the present erosion surface (129Wgr) and from the exhumed Upper Cambrian erosion surface (149gr). Both rocks are mechanically rather weak and lack the rigidity of fresher granite. A petrographic description of the material is included in the Appendix.

The weathered sample from the Texas quarry (128Wgr) is complementary to a fresh sample (128gr) taken from the same locality for comparison. A complete weathering profile exposed in a quarry wall shows highly decomposed granite at the top grading downward into completely fresh material at the base. The rock is typical of the coarse-grained Town Mountain granite. The chief weathering phenomenon appears to be a mechanical disaggregation which has thoroughly fractured the rock. Broken grains of feldspar and quartz which readily disintegrate into an arkosic gravel occur in the more weathered material. The only evidence of a chemical alteration is minor sericitization and kaolinization (?) of the feldspar and a local vermiculization of the biotite. Some iron oxide occurs along fractures and as a coating on the hornblende.

The second sample of weathered granite (149gr) comes from near the top of a buried dome which once rose several hundred feet above the general level of the Upper Cambrian erosion surface. The dome is presently being breached by Beaver Creek, which has cut approximately 20' into the granite. Although the upper few feet of the granite has been highly decomposed, relatively fresh looking material is exposed below about 10'. The sample used in this study came from an extensive outcrop about 15' below the projected top of the dome, which presently forms the bed of Beaver Creek. The rock lacks the elasticity of fresher material and several fracture surfaces coated with iron or manganese (?) oxides may represent exfoliation sheeting in the dome. This granite is less visually altered than the sample from the Texas quarry; however, its proximity to the old erosion surface makes it rather suspect. Both weathering phenomena at the time of near exposure in Upper Cambrian time and subsequent contact with meteoric water from the overlying Riley formation are possible causes of damage to the geochronologic systems. Effects due to present-day erosion may also have contributed to the mechanical and chemical alteration of the rock.

Microcline, biotite, and hornblende separates were taken from each of the rocks. The results of the Rb^{87}-Sr^{87} and K^{40}-Ar^{40} age determinations on these materials are given in Tables 2 and 3 and Plate II. It is immediately apparent that neither the microcline or the hornblende has suffered any change in age due to the

weathering of the granite. These ages are entirely consistent with those determined on fresh minerals from the area. The slightly varying amounts of potassium, rubidium, and strontium occurring in the weathered and fresh samples from the Texas quarry are believed to reflect original variations in chemistry or the purity of the mineral separates rather than changes brought about by the weathering. The ability of these minerals to give such a consistent age pattern, and, therefore, probably to remain a closed system, even upon exposure to rather severe chemical and physical weathering, is rather remarkable.

The Rb^{87}-Sr^{87} ages on the biotites were 955 and 925 million years for the Texas quarry and the Beaver Creek granites, respectively. Slight losses of radiogenic strontium (or gain in rubidium) appear to have occurred in these biotites. However, despite the rather severe nature of the weathering, especially in the sample of the Texas quarry granite, this effect has altered the resultant ages by less than 10%. No change in K^{40}-Ar^{40} ages were observed in the weathered biotites as compared to the fresh ones. The complete argon retention and only small Rb^{87}-Sr^{87} age change on these biotites is especially remarkable in the light of the much greater age lowering observed in the fresh looking, but anomalous biotites.

Common Strontium Minerals

An accurate value for the isotopic composition of the normal strontium initially incorporated into a mineral is necessary

in determining the Rb^{87}-Sr^{87} age of poorly radiogenic material. For example, an error of only 0.1% in the normal Sr^{87}/Sr^{88} ratio will produce an error of 1% in the age of a 10% radiogenic mineral. It is possible to determine the original isotopic composition of the strontium by analyzing rubidium-poor minerals from it and correcting the observed strontium isotopic ratios for the small amount of radiogenic Sr^{87} produced since the time of crystallization. This calculation, of course, requires the minerals to have remained closed systems since their time of crystallization.

The strontium isotopic composition was determined on six mineral phases from the Petrick quarry granite (3gr) which had unfavorable Rb/Sr ratios for age dating. These include oligoclase, exsolution albite from the microcline, hornblende, apatite, fluorite, and allanite. The resultant analytical data are presented in Table 6, along with the Sr^{87}/Sr^{88} ratios normalized to make $Sr^{86}/Sr^{88} = 0.1194$ and corrected for the Sr^{87} produced by rubidium decay in 1025 million years. Since all of these minerals give the same Sr^{87}/Sr^{88} value of 0.0843 to within experimental error, it has been assumed that this is the isotopic composition of the original strontium incorporated into the various phases of the granite at the time of formation. This value, therefore, has been used throughout the age calculations to correct for original or 'common' strontium in the mineral.

The strontium isotopic composition of the exsolution albite which occurs as perthitic intergrowths in the microcline is of

particular interest. If one assumes that the albite acquired its strontium from the microcline at the time of exsolution, and that this strontium was representative of that occurring in the feldspar, a limit to the length of time between original crystallization and exsolution can be made. This is true since radioactive decay of rubidium in the potassium feldspar continually produces radiogenic Sr^{87} and, thus, alters the isotopic composition of the strontium. Since an enrichment of 0.5% in Sr^{87} would be detectably outside of experimental error, the fact that the albite shows no such increase in its strontium isotopic composition suggests that exsolution took place within 50 million years of the time of crystallization. This result is compatible with the work of Kuellmer (1960), who has observed perthitic textures in a number of late Tertiary microclines from intrusive rocks.

Minerals from several other rocks were also analyzed for their common strontium isotopic composition. These results have been considered elsewhere in the text and will not be discussed in detail here. They include fluorite (3p-3) and albite (3p-4) from pegmatites in the Petrick quarry, a suite of minerals--oligoclase, apatite, and allanite--from the foliate granite (22Igr) near Lone Grove, and chlorite replacing biotite from the medium-grained granite (4gr) which occurs within the core of the pluton. Except for those cases in which there is some evidence for a later alteration of the strontium isotopic composition, all calculated original Sr^{87}/Sr^{88} ratios lie between 0.0841 and 0.0845. It appears

Table 6. Sr^{87}/Sr^{88} ratios in some common strontium minerals.

Rock	Mineral	Sr, ppm	Rb, ppm	Sr^{87}/Sr^{88} observed[1]	Sr^{87}/Sr^{88} original[2]
3gr	oligoclase	195	11	0.0846	0.0843±0.0002
	albite (exsolution in microcline)	140	27	0.0851	0.0842±0.0002
	hornblende[3]	34	23	0.0883	0.0845±0.0004
	apatite	120	3.1	0.0845	0.0844±0.0002
	fluorite	48	0.1	0.0844	0.0844±0.0002
	allanite	215	27	0.0849	0.0843±0.0002
3p-3	fluorite (1)	9	0.2	0.0870	0.0869±0.0002
	fluorite (2) leachable in HNO_3 (~2%)	80	5	0.0886	0.0886±0.0002*
	residue (~98%)	7	0.3	0.0849	0.0847±0.0002
3p-4	oligoclase	74	5	0.0849	0.0845±0.0002
4gr	chlorite[4]	70	170	0.0974	0.0846±0.0008
22Igr	oligoclase (1)	125	30	0.0860	0.0848±0.0002
	oligoclase (2) dissolved in HF in 15 min (~5%)	...	...	0.0861	.....
	apatite	105	6	0.0843	0.0841±0.0002
	allanite	235	46	0.0852	0.0842±0.0002

1 normalized to make $Sr^{86}/Sr^{88} = 0.1194$

2 corrected for radiogenic Sr^{87} produced by rubidium decay in 1025 million years (* uncorrected; inferred to be recent effect)

3 contains approximately 2% poikilitic intergrowth of biotite; the calculated composition of pure hornblende is 35 ppm Sr and 5 ppm Rb

4 contains approximately 5% biotite; the calculated composition of pure chlorite is 73 ppm Sr and 115 ppm Rb

that an isotopically fairly homogeneous strontium was incorporated into the magma of the pluton and that crystallization took place rapidly enough so that essentially no enrichment in Sr^{87} occurred between the time of initial solidification and the final, late-stage pegmatite formation and deuteric alteration. The slightly high initial Sr^{87}/Sr^{88} ratios calculated for the pegmatite miherals may reflect some addition of Sr^{87} produced by rubidium decay between the time of granite and pegmatite crystallization. The high Rb/Sr ratio of the bulk pegmatite (which is dominated by the composition of the microcline) could have permitted such a 0.5% increase in Sr in less than 10 million years.

Distribution of Potassium, Rubidium, Normal Strontium, and Normal Argon

In addition to the geochronological results, the large number of sample localities and mineral species used in this study makes possible the investigation of certain chemical and mineralogical trends in the area. In particular, one may examine the distribution of those elements involved in Rb^{87}-Sr^{87} and K^{40}-Ar^{40} age dating both within a single plutonic intrusive and between different igneous and metamorphic rocks of the Llano Uplift. The areal variations in elemental abundances and partitioning factors between various mineral phases should be complementary with hypotheses on the emplacement and evolution of granitic intrusives.

In order to study these effects, it is desirable to calculate pure mineral compositions. In some cases the mineral separates consist essentially of a pure phase; however, in other cases an appreciable correction is necessary to eliminate the effects of contaminating species. Table 7 gives the modal analyses of the various mineral separates as determined from grain mounts and oil emersion. The calculated potassium, rubidium, and normal strontium contents of the pure mineral phases are given in Table 8. Contamination from minor amounts of apatite, allanite, etc. makes it impossible to calculate a precise strontium content for the biotites; therefore, only a maximum limit is placed on this element.

The rubidium and strontium contents of the biotite and microcline from the granites of the Lone Grove pluton is seen to vary considerably from sample to sample. With the exception of the foliated granite (22gr), the rubidium content of the biotite and microcline from the coarse-grained, Town Mountain granite varies between 1120 and 605 ppm and 420 and 255 ppm, respectively. The strontium content of the microcline for these rocks varies between 120 and 225 ppm and shows an inverse relationship with the rubidium content. Although there are too few samples to establish a definite elemental distribution pattern throughout the coarse-grained granite, it appears that the rubidium content of the minerals tends to decrease toward the core of the pluton while the strontium increases. No comparable systematic

Table 7. Modal Analyses of Mineral Separates. Data determined from grain mounts and oil immersion and given in percent by volume. Q, quartz; M, microcline; A, secondary albite; P, plagioclase; B, biotite; H, hornblende; Mu, muscovite, including sericite; Ch, chlorite; Op, opaques; Ap, apatite; and Zr, zircon. The pegmatitic minerals are essentially monomineralic and are not included in this table.

Rock	Mineral	Mesh size	Q	M	A	P	B	H	Mu	Others	
3gr	microcline	35-80	0.1	98	1.4	0.1	0.0	0.0	0.0		0.0
	oligoclase	35-80	0.8	0.1	(a)	99	0.0	0.0	0.0		0.0
	biotite	35-80	0.2	0.1	0.0	0.0	88	9	0.0	2.8	Op, Zr, Ap
		80-115	0.0	0.0	0.0	0.0	97	2	0.0	1.1	Op, Zr, Ap
	hornblende	35-80	0.2	0.5	0.0	0.2	7	91	0.0	1.0	Ap, Zr, Op
50gr	microcline	80-115	0.1	99	0.4	0.1	0.0	0.0	0.0		0.0
	biotite	35-80	0.1	0.1	0.0	0.1	83	14	0.0	2.5	Op, Zr, Ap
	hornblende	35-80	0.1	0.3	0.0	0.2	10	89	0.0	0.9	Ap, Op, Zr
41gr	microcline	80-115	0.1	99	0.5	0.1	0.0	0.0	0.0		0.0
	biotite	35-80	0.1	0.1	0.0	0.0	91	7	0.0	1.7	Op, Zr, Ap, Ch
	hornblende	35-80	0.2	0.2	0.0	0.1	9	89	0.0	1.1	Ap, Op, Zr
128gr	microcline	80-115	0.1	100	0.3	0.0	0.0	0.0	0.0		0.0
	biotite	20-35	0.1	0.1	0.0	0.1	98	0.8	0.0	1.2	Op, Zr
	hornblende	80-115	0.1	0.0	0.0	0.0	2	98	0.0	0.3	Ap, Op, Zr
128Wgr	microcline	80-115	0.1	99	1.1	0.1	0.0	0.0	(b)		0.0
	biotite	20-35	0.1	0.1	0.0	0.1	98 (c)	1.0	0.0	1.1	Op, Zr, Ch
	hornblende	80-115	0.1	0.1	0.0	0.0	3	96 (d)	0.0	0.9	Op, Ap, Zr

(a) included with oligoclase, probably less than 2%

(b) microcline contains some sericite and clay material

(c) biotite incipiently altered to vermiculite

(d) hornblende contains iron oxide stains

Rock	Mineral	Mesh size	Q	M	A	P	B	H	Mu		Others
149gr	microcline	80-115	0.0	99	0.9	0.1	0.0	0.0	0.0		0.0
	biotite	20-35	0.0	0.0	0.0	0.0	97	2	0.0	1.3	Op, Zr, Ap
	hornblende	80-115	0.1	0.1	0.0	0.1	8	91	0.0	1.0	Ap, Op, Zr
22-Igr	microcline	80-115	0.0	99	0.7	0.1	0.0	0.0	0.1		0.0
	biotite	35-80	0.0	0.0	0.0	0.0	99	0.0	0.1	0.5	Op, Ap
22-IIgr	microcline	80-115	0.0	100	0.4	0.0	0.0	0.0	0.0		0.0
	biotite	35-80	0.0	0.0	0.0	0.0	99	0.0	0.1	0.4	Op, Ap
4gr	microcline	80-115	0.0	100	0.1	0.0	0.0	0.0	0.1		0.0
	muscovite	80-115	3	0.4	0.0	0.2	0.1	0.0	96	0.5	Ap, Zr
	biotite	80-115	0.0	0.0	0.0	0.0	68	0.0	0.2	32	Ch, Op
6gr	microcline	80-115	0.0	99	1.1	0.1	0.0	0.0	0.0		0.0
	biotite	35-80	0.0	0.0	0.0	0.0	98	0.0	0.0	1.7	Op, Zr, Ap
20gr	microcline	80-115	0.0	99	0.6	0.0	0.0	0.0	0.1		0.0
	muscovite	80-115	0.8	0.3	0.0	0.0	0.2	0.0	98	0.6	Ap, Zr, Op
	biotite	80-115	0.0	0.0	0.0	0.0	99	0.0	0.2	0.7	Op, Zr
53gn	microcline	80-115	0.0	99	0.8	0.1	0.0	0.0	0.0		0.0
	biotite	80-115	0.0	0.0	0.0	0.0	98	0.0	0.0	1.8	Op, Ch
25am	hornblende	80-115	0.4	0.0	0.0	0.7	0.0	99	0.0	0.3	Op, Ap
14rp-1	microcline	35-80	0.0	97	2.5	0.5	0.2	0.0	0.0		0.0
14rp-2	microcline	35-80	0.0	96	3.0	0.5	0.5	0.0	0.0		0.0

Table 8. Calculated potassium, rubidium, and normal strontium contents of the pure mineral phases.

Rock	Mineral	K, %	Rb, ppm	Sr, ppm
3gr	microcline	11.0	330	170
	oligoclase	0.42	11	195
	albite (secondary)	...	27	140
	quartz	0.0008	>0.05	>0.2
	biotite	6.8	915	>5
	hornblende	1.20	~5	35
	apatite	...	3.1	120
	fluorite	...	0.1	48
	allanite	...	27	215
3p-1	microcline	9.3	525	19
	biotite	6.9	2330	>3
			2010	>3
3p-2	biotite	7.4	2525	>2
3p-3	microcline	...	490	34
	biotite	6.7	2345	11
	fluorite	...	0.3	8
3p-4	microcline	...	395	48
	oligoclase	0.44	5.2	74
	biotite	7.2	1490	>4
	hornblende	1.19	...	...
50gr	microcline	11.4	275	225
	biotite	6.8	725	>5
	hornblende	1.27	...	...
41gr	microcline	...	300	200
	biotite	6.8	825	>5
	hornblende	1.26	...	...
128gr	microcline	...	420	120
	biotite	7.2	1120	>5
	hornblende	1.09	...	...
128Wgr	microcline	...	390	145
	biotite	6.9	1050	>5
	hornblende	1.10	...	...
149gr	microcline	...	255	225
	biotite	7.0	605	>5
	hornblende	1.44	...	...

Rock	Mineral	K, %	Rb, ppm	Sr, ppm
22Igr	microcline	11.5	350	135
	oligoclase	...	30	125
	biotite	7.6	1470	>5
	apatite	...	6.3	105
	allanite	...	46	235
22IIgr	microcline	11.9	365	135
	biotite	7.6	1565	>5
4gr	microcline	12.8	865	59
	muscovite	7.0	1000	52
	biotite	5.6	1415	>5
	chlorite	...	115	73
6gr	microcline	...	330	200
	biotite	7.4	955	>5
20gr	microcline	...	255	140
	muscovite	6.6	300	20
	biotite	6.5	570	>5
21p	muscovite	8.5	580	4.9
53gn	microcline	12.1	425	145
	biotite	7.6	1025	>5
25am	hornblende	0.25	...	...
14rp-1	microcline	...	335	135
14rp-2	microcline	...	300	71

variations in the potassium content of the minerals of these rocks appear to be present.

The foliated granite (22gr) and the medium-grained granite from the core of the pluton (4gr) show an enrichment in the rubidium content of their minerals over that found in the normal, coarse-grained, Town Mountain granite. The potassium content of the biotite from the foliated granite is several percent greater and that of the medium-grained granite is 20% lower than that of the coarse-grained granite. The pegmatitic minerals from the Petrick quarry also show a marked increase in their rubidium content and decrease in their common strontium content compared to the associated granite.

With the exception of the rhyolite porphyry (14rp), only one locality was sampled from each of the other rock types included in this study. The variable rubidium and strontium contents of the microcline from the rhyolite porphyry indicate that a considerable range in the trace element composition of this mineral is present.

For the six biotite-microcline pairs on which potassium and rubidium analyses were available for both minerals, it was possible to calculate a partitioning factor. This factor, $K_{bio\text{-}micr} \equiv (Rb/K)_{bio}/(Rb/K)_{micr}$, is a measure of the preferential rubidium to potassium concentration in biotite relative to microcline. The results of this calculation for the Petrick quarry (3gr), the Paint Horse quarry (50gr), the two fractions of the

foliated granite from Lone Grove (22Igr and 22IIgr), the medium-grained granite (4gr), and the Valley Spring gneiss (53gn) are given in Table 9. Assuming equilibrium between mineral pairs, it might be expected that to a first approximation such a factor would be only a function of temperature and fairly constant for chemically similar material. Despite the variation in lithologies included in Table 9, a rather narrow range for $K_{bio\text{-}micr}$ is encountered. The two samples of Town Mountain granite (3gr and 50gr), which are chemically and mineralogically quite similar, give a very good agreement in their partitioning factor. The highest Rb/K ratios in biotite relative to microcline occur in the foliated granite (22Igr and 22IIgr). It is interesting to note that a reduction in the rubidium content of these biotites would both tend to bring the partitioning factor in line with that found on the other rocks and also raise the anomalously low age of this mineral. In fact, a concordant Rb^{87}-Sr^{87} age for these biotites from the foliated granite would occur when enough rubidium is subtracted away to make their $K_{bio\text{-}micr} \simeq 4.4$, in good agreement with the other coarse-grained granites. This is suggestive of the recent addition of rubidium to the biotite; however, a better understanding of element partitioning between mineral phases is necessary before such a conclusion can be proven. Long (1959) discusses the ion exchange capacity of several minerals and suggests the possibility of some rubidium addition to biotites by ground water circulation.

A partitioning factor, $K_{bio\text{-}micr}$, can also be calculated

for the biotite and microcline from the Petrick quarry pegmatite (3p-1); however, it is not known if the analyzed minerals represent an equilibrium pair. Indeed, the wide variation in the rubidium content of the two biotite splits from this locality make the calculation of a unique factor impossible. The range in $K_{bio\text{-}micr}$ using the two biotite rubidium determinations of Table 8 is given in Table 9. No interpretation of this single pegmatitic pair is possible. However, the occurrence of a relatively high value for the distribution factor on a biotite which has a low Rb^{87}-Sr^{87} age is similar to the case of the foliated granite (22gr).

Two additional partitioning factors can be calculated for the Petrick quarry granite (3gr). These are: $K_{micr\text{-}olig} = 1.1_4$ and $K_{bio\text{-}hb} \simeq 32$. The former factor indicates that the acceptance of rubidium relative to potassium into the two feldspars is about equal. The latter factor shows a strong preference for rubidium relative to potassium to enter the biotite structure over the hornblende structure.

Samples 4gr and 20gr permit two calculations of $K_{bio\text{-}musc}$; the values of this partitioning factor are 1.7_8 and 1.9_3, respectively. The agreement between these two rocks is interesting since the muscovite in the former case represents secondary sericitic alteration.

As a comparison, values of $K_{bio\text{-}musc} = 1.7_1$ and $K_{bio\text{-}micr} = 2.3_7$ were obtained on pegmatitic minerals from the Snowflake mine in the Gold Butte area of southern Nevada (M. A. Lanphere, personal communication). An investigation of partitioning factors from

Table 9. Some values of the partitioning factor, $K_{bio\text{-}micr} \equiv (Rb/K)_{bio}/(Rb/K)_{micr}$, for biotite-microcline pairs.

Rock	$K_{bio\text{-}micr}$
3gr	4.49
50gr	4.42
22Igr	6.3_6
22IIgr	6.7_1
4gr	3.7_6
53gn	3.8_4
3p-1	5.1_7-6.0_0

numerous localities would be necessary in order better to establish their behavior. The present data suggest that variations of up to a factor of three can exist between mineral pairs from different rock types. A thorough study is necessary to see if a more uniform pattern can be obtained on individual rock types.

Regularities observed in the amount of normal argon obtained during the fusion of various mineral species suggests that most of this argon comes from the mineral itself rather than the extraction train. It was found that a certain quantity of normal argon was characteristically released per gram of each mineral. These quantities were: granitic biotite, 5-14 ppb; pegmatitic biotite, 18-25 ppb; hornblende, 1-4 ppb; microcline, 10-16 ppb; muscovite, 13-17 ppb; and plagioclase, 3-4 ppb. It is most probable that this argon was absorbed on the surfaces of the mineral. No outgassing of the sample was conducted prior to the extraction fusion.

Regional Interpretations

The exposed igneous and metamorphic rocks of the Llano Uplift are part of an extensive basement complex underlying much of central and western Texas (Flawn, 1956). The Pre-Cambrian rock of the so-called Texas craton was thought to be the oldest of the area. Younger Pre-Cambrian events were considered to have taken place against this stable mass. More recent geochronological work, however, by Wasserburg, Wetherill, Silver, and

Flawn (1962) has disproven this assumption. Most of the cratonic rocks of central and western Texas have been shown to have the youngest rather than the oldest radioactive ages. Rocks with ages ranging from 1000 to 1100 million years extend across the area and have been correlated with the Grenville rocks of equivalent age in eastern United States and Canada (Tilton, Wetherill, Davis, and Bass, 1960). The Llano Uplift is included in this belt and its general age pattern is compatible with the interpretation of Wasserburg, Wetherill, Silver, and Flawn (1962).

In detail, the Pre-Cambrian rocks of the Uplift show a complicated stratigraphic and structural history. An outline of the metamorphic and igneous events which have occurred in these rocks is described in the section on Regional Geology. The geochronological results of this study show that most of this fine structure which is recorded in field relationships has been lost in the mineral ages. Thus the metamorphic rocks of the Packsaddle formation and Valley Spring gneiss and the several granites representing different periods of emplacement all yield identical ages of 1000-1050 million years to within experimental error. Only a rhyolite porphyry shows a significantly younger age of about 910 million years in accord with geologic evidence. These data, therefore, either indicate a simultaneity of the various metamorphic and igneous processes to within less than 50 million years or else give some age not directly related to the rock crystallization. It is possible that some cooling off period related to

the cessation of orogenic processes or regional uplift may be the 'event' dated by these mineral ages. Under such a hypothesis the minerals would continue to lose their daughter isotopes until the rocks had become sufficiently cool to retain them.* In deep seated plutonic environments the time interval between mineral formation and daughter retention might be rather long and possibly different for each geochronological system. This effect could explain some of the age discrepancies reported between the K^{40}-Ar^{40}, Rb^{87}-Sr^{87}, and U-Pb dating methods.

If the rock remained a closed system to rubidium and strontium since its formation and only the minerals continued to lose or redistribute their daughter products, it is possible to estimate a maximum age for the system as a whole. Using the achondritic value of the Sr^{87}/Sr^{88} ratio for the isotopic composition of the original strontium, the Town Mountain granite as represented by the sample from the Petrick quarry could not be older than 1175 million years. More reasonable values of the original strontium isotopic composition would give even lower

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* In those cases where the total rock Rb^{87}-Sr^{87} ages do not exceed the individual mineral ages, two possible explanations present themselves which would still allow the rock to have an age younger than that of its crystallization. Either (1) the rock as a whole could have lost any radiogenic strontium formed or else (2) complete isotopic homogenization between the various mineral phases could have continuously occurred during this time interval between rock formation and age retention. In the latter case, any age calculated by using the 'normal' strontium isotopic composition obtained from common strontium minerals in the rock would date the time of age retention rather than crystallization.

ages. A total rock age of 1100 million years, or approximately 75 million years greater than the average mineral ages by the Rb^{87}-Sr^{87} method, would be a more probable estimate of the maximum age of the system.

Discrepancies of approximately 100 million years were found by Wasserburg, Wetherill, Silver, and Flawn (1962) between U-Pb ages on zircons and Rb^{87}-Sr^{87} and K^{40}-Ar^{40} ages on micas, hornblendes, and microclines. Their maximum age by these latter methods is 1090 million years while supposedly syngenetic zircons give ages on the concordia diagram of 1150-1200 million years. Several possible explanations for this difference in ages were presented by these workers. It was suggested that slight strontium and argon losses under near surface conditions could be responsible for this effect.

This investigation on extremely fresh material, however, still shows the same discrepant behavior between the methods. Aldrich, Wetherill, Davis, and Tilton (1958) give an analysis for a zircon from the Petrick quarry which yields an age on the concordia diagram similar to the ones found by Wasserburg, Wetherill, Silver, and Flawn (1962). In addition to being at least 100 million years greater than the other mineral ages, this zircon is older than a reasonable estimate of the total rock Rb^{87}-Sr^{87} age. This would suggest that either a wrong value for the decay constants has been used or else radiogenic Sr^{87} has escaped from the granite during its early history.

CONCLUSIONS

By using refined chemical and mass spectrometric techniques, it is possible to achieve a precision of ± 1½% in the Rb^{87}-Sr^{87} ages of highly radiogenic minerals. In addition, by normalizing the Sr^{86}/Sr^{88} ratio of the mineral strontium, it is possible to improve the dating of poorly radiogenic samples. The least radiogenic sample included in this study, a microcline having a Sr^{87} enrichment of only 7%, is believed to yield an age with a precision of ± 4½%. Minerals dated by the K^{40}-Ar^{40} method yielded argon which was over 85% radiogenic and gave ages having a precision of ± 1% in all cases except those with low potassium content where the lowest precision was ± 2%. Within these limitations of experimental uncertainty, it is possible to evaluate the various geochronological systems for real effects.

The ages from the different minerals and sample localities are summarized on Plate II. These data suggest that except for the rhyolite porphyry (14rp) all of the rocks are of similar age within experimental error. Excluding those determinations which yielded obviously anomalous results, the average mineral ages along with their maximum spread are as follows:

	Rb^{87}-Sr^{87} ages	
Microcline:	1025 my	(980-1065 my)
Muscovite:	1050 my	(1035-1075 my)
Biotite:	1010 my	(975-1025 my)*

* If one excludes the somewhat incipiently weathered granite, 41gr, the biotite age becomes 1020 my (1005-1025 my).

K^{40}-Ar^{40} ages

Muscovite:	1055 my	(1020-1080 my)
Biotite:	1045 my	(1025-1075 my)
Hornblende:	1045 my	(980-1080 my)

Since all of these methods give ages which are grouped within a time interval commensurate with the experimental error, it is difficult to place a true minimum spread on the various mineral ages. Assuming the age spreads obtained from the analyses are a real indication of the mineral's ability to record an event, we see that ranges of 8%, 4%, and 5% occur in the Rb^{87}-Sr^{87} ages on microclines, muscovites, and biotites, respectively. The K^{40}-Ar^{40} ages show ranges of 6%, 5%, and 10% on muscovites, biotites, and hornblendes, respectively. Except for the muscovites where the age pattern is biased by the peculiar behavior of the secondary sericite from the medium-grained granite (4gr), the various minerals give very consistent ages by each of the two methods.

The mean Rb^{87}-Sr^{87} age is 1015 million years and the mean K^{40}-Ar^{40} age is 1045 million years. The significance of this 3% disparity, which appears to be a real effect, is not clear. Until better determinations of the decay constants are available, it is not possible to give a unique interpretation of this effect. Assuming that the two geochronological systems keep identical time, it is possible to determine their relative decay rates. If we assume the K^{40} decay constants to be correct, the decay

constant of Rb^{87} should be decreased by 3% in order to bring the two dating systems into best concordance. This is equivalent to using a Rb^{87} half-life of $48._5 \times 10^9$ years, which is midway between the values of Flynn and Glendenin (1959) and Aldrich and Wetherill (1958). It is, of course, also possible that the two geochronologic systems do not begin keeping time simultaneously or that slight diffusive daughter loss occurs in one of them. In such cases one would not expect exactly the same ages to result from both methods.

K^{40}-Ar^{40} ages on microclines and plagioclases from these rocks appear to be consistently 5-20% lower than those obtained by the other minerals. These low ages can be attributed to the diffusive loss of argon from the feldspars.

Two microclines from a rhyolite porphyry give Rb^{87}-Sr^{87} ages of 890 and 935 million years. The average age of 910 million years is 100 million years younger than the other microcline ages and is significantly outside of experimental error from them. These data suggest that two events separated by such a 10% interval can be distinguished if the latter event does not noticeably affect the older one.

A problem associated with the interpretation of mineral ages is the actual meaning of the 'age'. It is doubtful that a mineral would be capable of quantitatively retaining its radiogenic daughter at the elevated temperature prevalent immediately upon

crystallization. In the case of deep-seated plutonic rocks where a significant time interval may separate mineral crystallization and rock cooling, this problem becomes especially difficult. A maximum age for which a system could have existed with its present Rb/Sr ratio can be calculated by using a reasonable estimate for the isotopic composition of the original strontium. It is, however, in general not possible to relate the mineral ages to a specific phenomenon, e.g., time of crystallization, time of uplift, etc. It is most probable that daughter retention begins over some integrated time interval in the rock's cooling history. If orogenic processes occur at such a rate that rock formation and subsequent cooling take place in a geologically short period of time (less than 20 million years), the effect would not be serious in 1000 million year old rocks. A young intrusive would be more suitable for observing the detailed age pattern of an orogenic cycle. Laboratory determinations of argon and strontium diffusion in the various minerals should complement such a study.

Curtis, Evernden, and Lipson (1958) have made a study of a granitic intrusion complex from a portion of the Sierra Nevada batholith. Using K^{40}-Ar^{40} ages on micas, they subdivide the multiple pluton into several bodies ranging in age from 77 to 95 million years. They conclude that the average interval of time between intrusions is approximately 2 million years. However,

since such an age differential is approximately equal to their stated experimental error, it is doubtful that the details of this age pattern are justified. Analyses of different samples from the same intrusive body should be run in order to see if the same age is found. Also, the effect of later intrusions upon the age of the older rocks is not considered by them.

During the course of this study, a number of anomalous biotite ages were observed. Biotites from obviously weathered granite (128Wgr and 149gr) gave good K^{40}-Ar^{40} ages, but Rb^{87}-Sr^{87} ages from 5-10% low. A suite of pegmatitic biotites (3p) gave both low K^{40}-Ar^{40} and Rb^{87}-Sr^{87} ages, but the latter were always considerably more discrepant. Biotite from a coarse-grained, foliated granite (22gr) gave good K^{40}-Ar^{40} ages, but low Rb^{87}-Sr^{87} ages. Anomalies of up to 35% in their Rb^{87}-Sr^{87} ages were present in the latter two groups of biotites. The mechanism responsible for these low ages is poorly understood. The fact that much greater discordances occur in fresh rather than obviously weathered rock suggests that ordinary surface weathering is not the sole cause of these anomalies. Some peculiar effect of hydrothermal or meteoric water or an imperceptible metamorphism are possible candidates for this phenomenon. In principle either strontium loss or rubidium gain could have caused the low Rb^{87}-Sr^{87} ages, and argon loss or potassium gain could have caused the low K^{40}-Ar^{40} ages. However, since definitive evidence for radiogenic strontium mobility

has been found, it is most probable that daughter loss has produced these low Rb^{87}-Sr^{87} ages. It would also be more likely that argon loss has produced the low K^{40}-Ar^{40} pegmatitic biotite ages.

Anomalous common strontium was encountered in a fluorite from a Petrick quarry pegmatite (3p-3). However, unlike the situation cited by Compston and Jeffery (1959) where it appears that radiogenic strontium actually entered the crystal lattices of epidote and apatite during a period of rock metamorphism and reconstitution, the anomaly in this case was traceable to a surficial incrustation of carbonate (?) containing the enriched strontium. It is possible that this material contains some of the radiogenic strontium lost from the adjacent biotite. In any case, this incident is evidence for the mobility of radiogenic strontium from its initial site of production without metamorphism.

An analysis of the constituent minerals and the total rock from the coarse-grained, foliated granite showed that if this low biotite age was due to daughter loss, the radiogenic strontium was not only removed from the mineral but also to a large extent from the entire rock. Under such open system conditions, the resultant Rb^{87}-Sr^{87} total rock age is too low and no longer gives the initial rock age.

Minerals having low Rb/Sr ratios--oligoclase, secondary albite, hornblende, apatite, fluorite, and allanite--from several rocks included in this study were analyzed for their rubidium

and strontium contents and strontium isotopic composition. Assuming an age of 1025 million years for the rocks, a correction for subsequent rubidium decay was applied and the initial isotopic composition calculated. All strontium data were normalized to $Sr^{86}/Sr^{88} = 0.1194$, and the resultant Sr^{87}/Sr^{88} ratios fell within the range 0.0841-0.0845 for the primary granitic minerals. An average value of 0.0843 ± 0.0002 has been used in calculating the mineral ages.

The number of samples included in this study has made it possible to look at the potassium, rubidium, and normal strontium distribution within some of the rocks of the area. Several partitioning factors involving the Rb/K ratio were calculated for mineral pairs from a particular sample. A further study of such geochemical distribution of elements between various mineral phases and different localities may yield information concerning the rock's genesis.

APPENDIX

Description of Samples

The samples which were used in this study have been collected from quarries and road exposures throughout the Llano Uplift. A detailed petrologic description of this material is given below.

3 - Petrick Quarry: (Town Mountain granite)

The Petrick quarry is situated within a low, domical outcrop of granite two miles west of Buchanan Dam at the intersection of Texas highways 29 and 261. Keppel (1940), Goldich (1941), and Barnes, Dawson, and Parkinson (1947) have described the granite and related pegmatites and aplites from this locality. The two former workers also give chemical analyses of the granite. Figure 2 is a sketch map of the quarry showing the location of the samples included in this study.

Granite: The granite (3gr) used in this study was taken from a freshly exposed ledge lying 10' below the present quarry rim and approximately 20' below the original surface of the dome. The rock is grayish-pink, coarse-grained, and seriate porphyritic in texture. It is composed of microcline, oligoclase (Ab_{73}), quartz, biotite, hornblende, and a suite of accessory minerals which includes opaques, sphene, zircon, allanite, apatite, and fluorite. A small amount of sericite formed by the alteration of feldspar is the only secondary mineral present in the fresh rock. A modal analysis of the granite is given in Table 10.

The potash feldspar consists of pink to orange, subhedral

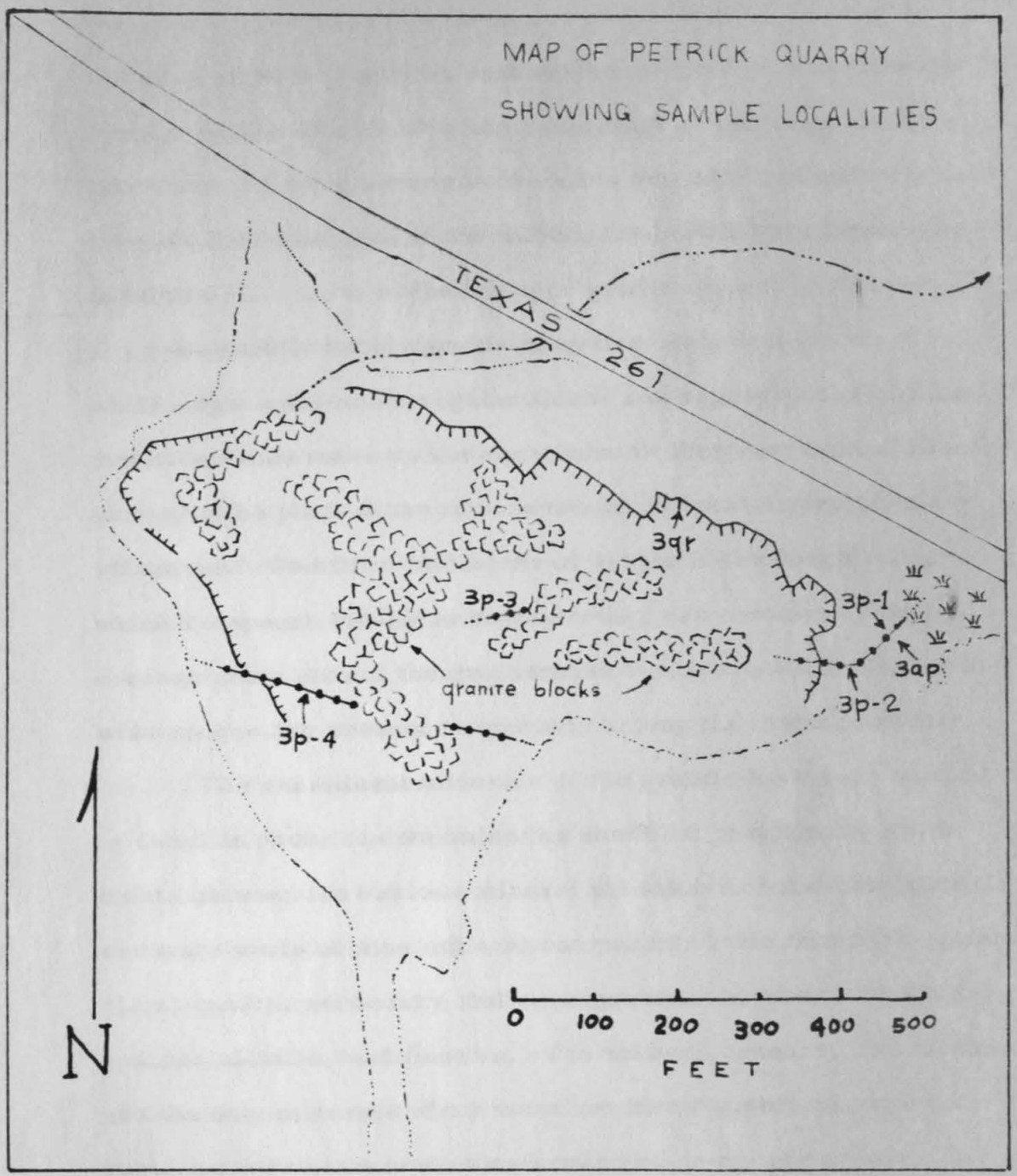

Fig. 2. Sketch map showing location of samples from the Petrick quarry. 3gr, granite; 3ap, aplite; 3p-1, 3p-2, 3p-3, and 3p-4, pegmatites.

grains of perthitic microcline which range in size from that of the groundmass up to 36 mm in maximum length. Exsolution lamellae of albite occur throughout the microcline and make up approximately 20% of the grain. Rapakivi and antirapakivi textures with pearly gray oligoclase rims or cores respectively are frequently encountered in the microcline. Poikilitic inclusions of biotite and quartz in the feldspar grains are not uncommon. Clear to slightly bubbly grains of quartz, anhedral grains of white oligoclase, and irregular flakes and aggregates of biotite and hornblende make up the remainder of the groundmass. Some zoning in the plagioclase is present, as is local myrmekitic development. Poikilitic inclusions of biotite in the hornblende, which it appears locally to be replacing, are common. The average grain size of the groundmass is about 6-8 mm, although wide ranges are present, especially among the mafic minerals.

The constituent minerals of the granite have been studied in detail in order to determine the chemical partitioning which exists between the various mineral phases. At least partial analyses were made on nine mineral components from this rock--microcline, quartz, secondary albite, oligoclase, biotite, hornblende, apatite, allanite, and fluorite. The sphene, opaques, and zircon are the only minerals which were not investigated. A total rock rubidium-strontium analysis was also made on this granite.

Aplite: Dikes of aplite genetically related to the granite are common throughout the quarry. The aplite is often associated with pegmatite, which commonly occurs in swellings along the

center of the dikes.

The aplite (3ap) was collected from one of such dikes which has been exposed by quarrying (see Figure 2). The rock is light grayish pink in color and has a sugary texture. Albite (Ab_{93}), microcline, and quartz are the chief components of the rock, while biotite and fluorite occur in accessory amounts. A small amount of secondary chlorite and calcite are also present.

The minerals are rather uniform in size, averaging about 1 mm in diameter, and occur as subhedral, interlocking grains. A slight planar structure is often developed in the aplite which parallels the contacts of the dike, but this foliation appears to be more of a mineral segregation than a kinematic effect.

A total rock rubidium-strontium analysis was made on this rock.

Pegmatite: Numerous pegmatite dikes have been encountered during the quarrying of the Petrick quarry. Material from four sample localities representing three separate pegmatitic bodies have been collected. Each of the localities was in freshly exposed rock which showed no evidence of weathering. Two of these pegmatites consisted chiefly of coarse-grained quartz and microcline with intergrown books of biotite, while the third included, in addition to these minerals, a more basic phase which contained crystals of plagioclase and hornblende up to several inches in dimension. All of the pegmatites occur as long linear dikes bordered on both sides by aplite which in turn grades into the normal granite.

Table 10. Modal analyses of some granites and gneiss. Samples 3gr, 50gr, 128gr, 41gr, 149gr, 22gr, and 4gr are granites from the Lone Grove pluton. Sample 6gr is Oatman granite, sample 20gr is Sixmile granite, and sample 53gn is Valley Spring gneiss. All modes are given in volume percent.

	3gr	50gr	41gr	128gr	149gr
Quartz	29.8	29.3	26.2	31.3	28.9
Microcline	28.5	33.1	29.1	28.4	28.1
Albite (secondary)	7.3	9.4	12.4	4.4	6.5
Oligoclase	24.8	21.7	22.1	26.2	26.7
Biotite	4.5	3.3	6.5	4.5	4.0
Hornblende	4.7	2.4	3.1	4.8	4.9
Muscovite (incl. sericite)	tr	0.2	tr	tr	0.1
Chlorite	tr	0.2	0.1	tr	0.3
Zircon	0.1	0.1	0.1	0.1	0.1
Allanite	0.2	0.2	0.3	0.2	0.2
Apatite	0.1	0.1	0.1	0.1	0.1
Sphene	tr	tr	tr	tr	tr
Opaques	tr	tr	tr	tr	0.1
Fluorite	tr	tr	tr	tr	tr
Calcite	--	--	--	--	--
Pyrite	--	--	--	--	--

Table 10 (continued).

	22gr	4gr	6gr	20gr	53gn
Quartz	27.9	33.3	33.1	37.2	27.7
Microcline	39.5	31.5	34.2	38.8	47.6
Albite (secondary)	3.5	0.4	2.8	1.2	--
Oligoclase	21.0	31.0	25.8	18.3	17.0
Biotite	7.2	1.8	3.1	3.5	4.5
Hornblende	--	--	--	--	--
Muscovite (incl. sericite)	0.3	0.5	0.2	0.6	0.4
Chlorite	0.2	1.4	0.3	0.2	0.2
Zircon	tr	tr	tr	tr	tr
Allanite	0.1	tr	tr	tr	--
Apatite	0.1	tr	0.1	0.1	0.1
Sphene	tr	tr	tr	tr	--
Opaques	tr	0.1	0.2	0.1	2.4
Fluorite	--	tr	tr	--	--
Calcite	--	tr	0.2	--	0.1
Pyrite	0.2	--	--	tr	--

Pinkish-orange microcline and milky bull quartz form the bulk of the pegmatite dikes, while books of black biotite lie both along grain boundaries and enclosed within single feldspar or quartz grains. The microcline forms subhedral to euhedral perthitic crystals ranging up to a foot or more in dimension. The biotite occurs in crystals up to 10" across and several inches thick although parting fractures generally limit the size of individual books to 1-3". Freshly exposed cleavage faces of the mica generally produce a distinct iridescence, and only locally along parting surfaces do ferric oxide stains suggest any alteration. A pocket containing fluorite and gadolinite was encountered in one of the pegmatites. The fluorite was pale yellow to greenish-yellow in color and had well-developed octahedral cleavage. The more basic pegmatite contains coarse, white grains of sodic oligoclase (Ab_{88}) and dark brownish-green, prismatic hornblende in addition to quartz, biotite, and microcline. The plagioclase shows strong albite twinning and contains numerous poikilitic inclusions of biotite, microcline, and quartz. The hornblende forms elongate crystals which often abound in intergrowths of biotite. The plagioclase and hornblende seem to be related to the adjacent aplite and may represent a coarsening in grain-size of it.

Samples of biotite and microcline (3p-1) representing a composite of several crystals were obtained from one of the acid pegmatites during the initial field season. When a serious discordancy was encountered in the biotite age, additional material was collected the following year. From this same pegmatite single

crystals of biotite and microcline (3p-2) were obtained from within a large, freshly broken mass of quartz in order to minimize the possibility of alteration due to direct exposure to meteoric water. Biotite, microcline, and fluorite (3p-3) from a second acid pegmatite were also collected, as was a suite consisting of microcline, plagioclase, biotite and hornblende (3p-4) from the more basic pegmatite.

50 - Paint Horse Quarry: (Town Mountain granite)

The Paint Horse quarry is located on the Fitzsimons Land and Cattle Company ranch approximately 2 miles southeast of Lone Grove. The quarry has been opened on a low granite mass which crops out extensively over the area. Barnes, Dawson, and Parkinson (1947) have included this granite in their description of the building stones of central Texas.

The granite (50gr) used in this study was taken from the floor of the quarry approximately 15 feet below the outcrop surface. The rock is grayish-pink, coarse-grained, and somewhat non-seriate porphyritic in texture. It is composed of microcline, oligoclase (Ab_{75}), quartz, biotite, hornblende, and accessory amounts of opaques, sphene, zircon, allanite, apatite, and fluorite. Minor amounts of secondary sericite and carbonate are associated with the feldspars and incipient chloritization of the biotite has occurred. A modal analysis of the granite is given in Table 10.

The microcline is pink in color and shows distinct perthitic intergrowths of albite. Individual phenocrysts have an average

grain-size of 20 mm with maximum lengths of approximately 42 mm. The rock displays a texture about midway between the seriate and non-seriate types. Although a bimodal distribution exists, there is still a continuum in feldspar grain-size between the groundmass and the phenocrysts. Exsolution lamellae of albite make up 25% of the perthite and occasionally form larger patches which suggest that considerable migration took place during unmixing. Rapakivi and antirapakivi textures are common, especially in the larger phenocrysts. In addition to the microcline, the groundmass consists of clear to slightly bubbly quartz, including numerous composite and semi-composite grains, anhedral, white oligoclase, and clusters of biotite and hornblende. The average grain-size of these minerals is about 8 mm, although some of the mafic aggregates are considerably larger.

Microcline, biotite, and hornblende separates were obtained from this rock.

41 - Golden Beach: (Town Mountain granite)

Coarse-grained porphyritic granite was collected from a road cut along Texas highway 261 approximately 4 3/4 miles north of the intersection with Texas highway 29. Here a low ledge of rock lying directly opposite the entrance to Golden Beach, a new resort development, is exposed along the west side of the road. This is locality B of Keppel (1940), which he included in his study of the pluton to represent typical coarse-grained porphyritic granite.

The granite (41gr), which was sampled from 4' below the top of the ledge, appears to be rather fresh and unweathered, although it lacks the strength and rigidity of some material obtained at greater depth. It is grayish pink, coarse-grained, and non-seriate porphyritic in texture. Microcline, oligoclase (Ab_{73}), quartz, biotite, and hornblende are the major constituents of the rock, while opaques, sphene, zircon, allanite, apatite, and fluorite occur in accessory amounts. The only secondary minerals are sericite and a trace of chlorite which represent alteration of the feldspar and biotite respectively. A modal analysis of the granite is given in Table 10.

The microcline is light pink in color and contains perthitic intergrowths of albite. The microcline occurs both in the groundmass and as phenocrysts, although it is possible to find some grains representing all gradations between the two. The phenocrysts range up to 50 mm in length with an average size of 25 mm, while the groundmass grains average 8 mm. The majority of the microcline occurs as phenocrysts, commonly with plagioclase to form rapakivi and antirapakivi textures. Exsolution lamellae and patches of albite make up approximately 30% of the perthite and indicate that a considerable quantity of soda was contained in the original microcline. Quartz, oligoclase, biotite, and hornblende form the bulk of the remaining groundmass. The mafic minerals generally occur in clusters of aggregate grains, many of which show varying stages of replacement of the hornblende

by biotite. The average grain-size of the groundmass is 8-10 mm, although a wide range in size is present. The rock has a poorly developed vertical flow foliation which strikes approximately east-west throughout the outcrop.

Microcline, biotite, and hornblende separates were obtained from this rock.

128 - Texas Quarry: (Town Mountain granite)

The Texas quarry is situated on a low, extensive outcrop 1/4 mile south of Texas highway 29 and 4 1/4 miles west of Buchanan Dam. Several openings situated within 1000' of the southern border of the pluton have been made into the granite. Numerous aplites, pegmatites, and xenoliths are included in the intrusive; however, the bulk of the rock shows no evidence of contamination from the adjacent schists. A complete weathering profile is exposed in one of the quarry walls. Highly decomposed granite at the top of the outcrop grades downward into completely fresh material. A sample of weathered granite (128Wgr) from the surface and fresh granite (128gr) from the base 12' below were collected from this locality.

The granite, which ranges from light grayish-pink when weathered to a deeper grayish-pink when fresh, is coarse-grained and seriate porphyritic in texture. Its primary constituents include microcline, oligoclase (Ab_{76}), quartz, biotite, hornblende, and accessory amounts of opaques, sphene, zircon, allanite, apatite, and fluorite. A modal analysis of the fresh granite is given

in Table 10.

The fresh granite contains pink, perthitic microcline with albite exsolution lamellae making up 15% of the grain. The microcline ranges in grain-size from that of the groundmass up to 32 mm in length; the larger phenocrysts commonly display rapakivi and antirapakivi textures. The quartz is relatively free of inclusions and shows a straight to slightly undulatory extinction. The oligoclase is pearly gray and devoid of extensive cloudy alteration. Brownish biotite and greenish hornblende occur as individual grains and aggregates throughout the rock. Minor sericite and only a trace of chlorite are present as secondary minerals in the unweathered rock.

The weathered granite appears to have suffered chiefly from a mechanical disaggregation. Fractures which transect broken feldspar and quartz grains abound throughout the rock and permit it to disintegrate into an arkosic gravel. Otherwise, the quartz is unaffected and only minor sericitization and kaolinization (?) of the feldspar have occurred. The biotite is predominantly fresh and unaltered, and only locally has about 10% of it been changed into bronze-colored vermiculite (?). The hornblende is also unweathered except for a brownish-red iron oxide coating on some of the grains. A secondary, opaque material, probably an iron oxide, is locally present as a vein filling in some of the fractures.

Microcline, biotite, and hornblende separates were obtained from both the fresh and weathered granite.

149 - Beaver Creek: (Town Mountain granite)

The top of a buried granite dome, which extends above the general Upper Cambrian erosion surface, is presently being breached by Beaver Creek. Stratigraphic evidence indicates that this feature rises several hundred feet above the base of the surrounding Paleozoic sediments. This locality, which has been described in detail by Barnes (1956), is situated approximately 1 3/4 miles north (upstream) from the secondary road bridge across Beaver Creek along the north shore of Buchanan Lake. The dome has only been eroded to a depth of about 20', and is clearly overlapped on all sides by Upper Cambrian sediments. Although the upper few feet of the granite show severe alteration, relatively fresh rock is encountered at a depth of only 10'. A modal analysis of the granite is given in Table 10.

Granite (149gr) from this locality was sampled to determine if the geochronologic systems of rock lying near the ancient erosion surface had been affected. Fresh material exposed in the stream bed and lying 15' below the projected top of the dome was obtained for this study. The rock is grayish pink, coarse-grained, and seriate porphyritic in texture. It is composed of microcline, oligoclase (Ab_{75}), quartz, biotite, hornblende, and accessory amounts of opaques, sphene, zircon, allanite, apatite, and fluorite. Small amounts of secondary sericite and chlorite formed from the alteration of feldspar and biotite are present. Locally, sheeting surfaces which may represent exfoliation layers in the dome contain thin coatings of manganese oxides (?).

The microcline is light pink in color and ranges in size from that of the groundmass up to 32 mm in maximum length. It contains approximately 20% exsolution albite, which occurs as lamellae, patches, and sinuous veinlets throughout the grain. Although some rapakivi and antirapakivi textures are present in the rock, they are less developed in this granite than most of the others from the Lone Grove pluton. Quartz, oligoclase, and clusters of the mafic minerals make up the remainder of the groundmass. The hornblende shows a partial alteration to biotite in which individual crystals of the hornblende commonly host many centers of replacement. Rounded grains of quartz are commonly inclosed in the hornblende, producing a peculiar texture not observed elsewhere in the pluton.

Microcline, biotite, and hornblende separates were obtained from this rock.

22 - Lone Grove: (Gray, foliated granite)

Coarse-grained, foliated granite was collected from a road exposure in Lone Grove. Fresh rock is exposed along the south side of Texas Ranch Road 2241 approximately 0.2 miles east of the bridge across the Little Llano River. The granite contains a distinct foliation which has a vertical dip and strikes roughly parallel to the border of the pluton.

A block of granite (22gr) from this outcrop measuring 12" x 10" x 8" was divided into halves and treated as two individual samples in order to see if any local variations in the geochronological systems were detectable. The rock is pinkish gray,

coarse-grained, and porphyritic in texture. Microcline, oligoclase (Ab_{80}), quartz, and biotite make up the bulk of the rock, while opaques, sphene, zircon, allanite, and apatite occur in accessory amounts. Sericite and a trace of chlorite are the chief secondary minerals. Pyrite is also observable throughout the granite; however, the genetic nature of this sulfide mineralization is not known. A modal analysis of the granite is given in Table 10.

The microcline is pale pink in color and ranges in size from that of the groundmass up to 30 mm in maximum length. Rapakivi texture is essentially absent in the feldspar and albite exsolution lamellae make up less than 10% of the microcline. Incipient sericitization of the feldspars is commonly developed, and a few small muscovite grains of possible primary origin are also present. Clear, unstrained quartz, albite-twinned oligoclase, and brown biotite form the remainder of the groundmass. The average grain-size of the rock is 2-4 mm; however, a continuous range in size up to that of the largest phenocrysts is present. Accessory minerals are less abundant in this rock than in the normal coarse-grained granite. A well-developed orientation of the mica and feldspar gives the rock its foliated texture. A few broken grains suggest that cataclastic deformation may have been partially responsible for this texture; however, the rock appears to have inherited most of its planar structure from primary flowage.

Microcline and biotite were obtained from both fractions of

the rock (22Igr and 22IIgr), and oligoclase, apatite, and allanite were obtained from the former fraction (22Igr) only. A total rock rubidium-strontium analysis was also made on 22Igr.

4 - Bluffton: (Red, medium-grained granite)

Medium-grained granite was collected from a road cut along Texas highway 261 approximately $1\frac{1}{2}$ miles east of Bluffton. Fresh granite occurs along the east side of the highway where it was exposed during road construction. This is locality C of Keppel (1940), which he used to represent medium-grained granite in his study of the pluton.

The granite (4gr) was sampled from the base of this outcrop where it showed no evidence of weathering. It is a reddish-pink, medium-grained rock composed predominantly of quartz, microcline, plagioclase (Ab_{91}), and biotite. Minor amounts of accessory opaques, sphene, zircon, allanite, apatite, and fluorite are also present. Deuteric alteration has produced some secondary chlorite, sericite, and magnetite in the rock. A modal analysis of the granite is given in Table 10.

The microcline has a typical quadrille structure; however, in contrast to the coarse-grained granites, it shows little evidence of perthitic intergrowths with albite. The feldspar grains are generally clear to partly cloudy where incipient sericitization has occurred. In addition, a few plagioclase grains have been locally replaced by carbonate. The plagioclase is a sodic albite with well developed albite twinning and local myrmekitic texture. The biotite

is dark brown and occurs as individual grains and localized aggregates. Although unaltered crystals of biotite are found, they are commonly partially to completely replaced by chlorite and magnetite, or, to a lesser degree, coarse-grained sericite. Some of the coarser grains of white mica may be primary muscovite; however, the bulk of it represents a replacement of biotite and feldspar. Although a rather wide range (0.1-3 mm) exists, the average grain-size of the rock is about 1.5 mm. Making up less than a percent of the granite are occasional euhedral to subhedral phenocrysts of microcline and, more rarely, quartz, which may exceed 15 mm in length.

Microcline, biotite, chlorite, and sericite separates were obtained from this rock.

6 - Oatman Creek: (Oatman granite)

Granite is exposed in the stream bed of Oatman Creek one mile southeast of Llano along Texas highway 71. Fresh rock has been encountered during the construction of a new highway bridge across the creek. Material from this locality was chosen to represent the medium-grained, gray to pink, cataclastic Oatman granite of Stenzel (1934).

The granite (6gr) was obtained from a freshly exposed outcrop directly under the bridge. The rock is dark grayish pink, medium-grained, and massive in texture. It is composed of microcline, oligoclase (Ab_{74}), quartz, and biotite with accessory amounts of opaques, zircon, and apatite. Secondary sericite with occasional

flakes up to 1 mm in diameter, discrete grains and patches of carbonate, and chlorite replacing biotite occur throughout the rock. A modal analysis of the granite is given in Table 10.

The cataclastic nature of this rock is quite evident in thin section. Feldspar and quartz grains are commonly broken and badly strained. Many semi-composite and composite quartz grains having a marked undulatory extinction are present. The feldspars are frequently cloudy showing considerable alteration to sericite and carbonate. Veinlets of sericite also commonly occur filling the fractures between broken grains. Albite exsolution in the microcline is not abundant, and appears to have been mainly replaced by the sericite. Some myrmekitic intergrowth of the plagioclase and quartz is present. The biotite is greenish brown in color, and has been locally somewhat shredded and, to a small extent, altered to chlorite. The average grain-size of the rock is 2-4 mm; however, pink microcline grains up to 10 mm in length are common throughout the rock. The individual grains are quite equidimensional and show no evidence of a preferred orientation.

Microcline and biotite separates were obtained from this rock.

20 - Kansas City Quarry: (Sixmile granite)

The Kansas City quarry is located 1 3/4 miles west of Llano along the north side of Texas Ranch Road 152. Material from this locality was chosen to represent the medium- to fine-grained, gray, Sixmile-type granite of Stenzel (1934). Barnes, Dawson, and Parkinson (1947) include a brief description of this locality in their

investigation.

The granite (20gr) used in this study was taken from a fresh exposure near the floor of the quarry. The rock is gray in color, medium-grained, and weakly foliated. It is composed predominantly of microcline, oligoclase (Ab_{75}), quartz, biotite, and a small amount of muscovite. Accessory minerals are not abundant and include opaques, zircon, and apatite. Sericite is common in the feldspars and produces cloudy areas in both the microcline and oligoclase. Chlorite is present in small amounts replacing biotite. Pyrite is also locally present in the rock. A modal analysis of the granite is given in Table 10.

The microcline is pale pink in color and contains 1-5% exsolved albite. Oligoclase grains commonly show albite twinning and rarely myrmekitic intergrowth with quartz. The quartz generally forms semi-composite grains with a pronounced interlocking texture with the other minerals. Reddish-brown biotite and irregular flakes of muscovite up to 2 mm in length make up the rest of the groundmass. The average grain-size of the rock is 3-4 mm, although some feldspar grains up to 8 mm in length are present. The foliation is produced by the orientation of elongate feldspar, quartz, and mica grains. Sutured grain boundaries and somewhat strained quartz grains suggest that this texture is in part due to a regional metamorphism of the granite after its emplacement. The strike and dip of the foliation are parallel to the regional structure in the surrounding metamorphic rocks.

Microcline, biotite, and muscovite separates were obtained from this rock.

53 - Clear Creek: (Valley Spring gneiss)

Valley Spring gneiss (53gn) was collected from a road cut along the north side of Texas highway 29 approximately $4\frac{1}{2}$ miles east of Buchanan Dam and 11/4 miles east of the highway bridge across Clear Creek in Burnet County. This locality was chosen as representative of the gneiss, although wide variations in texture and mineralogy are found throughout the Uplift. Gneiss from this vicinity has been described and chemically analyzed by Barnes, Dawson, and Parkinson (1947).

The rock has an irregular, gneissoid texture composed of gray and pink bands 2 to 10 mm in thickness which are alternately enriched and deficient in biotite and opaques. Tightly interlocking grains of microcline, quartz, oligoclase (Ab_{80}), biotite, and opaques make up the bulk of the rock, while zircon and apatite occur in accessory amounts. Secondary minerals include sericite, carbonate, and chlorite. A modal analysis of the gneiss is given in Table 10.

The microcline is pink in color and contains no visible albite exsolution. Both the microcline and the plagioclase is commonly cloudy in areas, and show considerable sericitization and, to a much less extent, replacement by carbonate. The quartz consists of simple to composite grains with straight to slightly undulatory extinction. Albite and some Carlsbad twinning is present in the plagioclase, although it is often obscured by sericitization. Greenish-brown biotite flakes and irregular to subhedral

grains of opaques minerals (magnetite ?) occur throughout the gneiss, but are mainly concentrated in the darker bands. Sericitic muscovite with discrete flakes up to 0.2 mm in diameter is found throughout the rock in addition to its occurrence in the feldspar. A minor amount of chlorite is also present and probably represents an alteration of the biotite. All of the minerals and, in particular, the mica show an elongation in the direction of foliation. The grain-size commonly ranges between 0.1 and 0.5 mm, but occasional, coarse bands with grains up to 2 mm are locally present.

Microcline and biotite separates were obtained from this rock.

21 - Martin Creek: (Pegmatite in Valley Spring gneiss)

Valley Spring gneiss containing dikelets of quartz-microcline and quartz-microcline-muscovite pegmatite is exposed in a road cut along Texas highway 29 three miles west of the Mason-Llano county line in Mason County. Pegmatite at this locality was collected from the south side of the highway 1/4 mile east of the bridge across Martin Creek.

The pegmatites occur as dikes and stringers which roughly parallel the foliation in the gneiss. They range in size from a local coarsening in grain-size of the gneiss to distinct bodies 1' or more in width and several feet in length. There appears to be two types of pegmatites present, quartz-microcline dikes with individual crystals up to 12" in length and smaller quartz-microcline-muscovite stringers or "sweat" pegmatites. In all

cases, the pegmatites show a complete gradation in grain-size between their coarsest phase and that of the host gneiss. Similarities in mineralogy and texture between the gneiss and pegmatites suggest that they are approximately syngenetic in origin.

The pegmatite (21p) used in this study contains microcline, quartz, muscovite, and a minor amount of oligoclase. The microcline is reddish-pink in color and forms euhedral to subhedral crystals up to 2'' in length. The quartz is milky white to colorless and surrounds the feldspar in anhedral grains $\frac{1}{2}$ - 1'' in diameter. The muscovite occurs as subhedral crystals and booklets up to 1'' in diameter. Several grains of pearly white plagioclase also occur scattered throughout the pegmatite.

Muscovite has been obtained from this pegmatite for analysis.

25 - Pennington Creek: (Amphibolite from Packsaddle Formation)

A sequence of steeply dipping schists, marbles, calc-silicate rocks, and amphibolites of the Packsaddle formation are exposed in a road cut along Texas highway 29 in the vicinity of the bridge across Pennington Creek 6 3/4 miles west of Buchanan Dam. These rocks lie concordantly along the southwestern margin of the Lone Grove pluton and, to the east, form the metamorphic septum separating it from the Kingsland pluton.

A dark bluish gray amphibolite (25am) lying approximately 300' from the granite contact was collected. An approximate modal analysis of the rock shows it to contain 60% hornblende,

25% quartz, 14% andesine (Ab_{54}), and 1% opaques. A small amount of apatite was the only accessory mineral seen in thin section. The hornblende is pleochroic light yellowish-brown to green to dark brownish-green; it occurs as elongate prismatic grains ranging from less than 0.05 mm to 3 mm and averaging 1 mm in length. The larger crystals commonly show a composite structure which extinguishes over an angle of 15-20°. The quartz and plagioclase forms subhedral crystals averaging 0.2-0.5 mm in diameter with rather straight grain boundaries. The quartz shows a pronounced undulatory extinction and the andesine commonly has a well-defined albite twinning. The rock contains a weakly-developed foliation parallel to lithologic layering; and the elongate hornblende crystals produce a distinct lineation in the plane of foliation and plunge gently to the southeast.

A hornblende separate was obtained from this rock.

14 - Babyhead: (Llanite, or rhyolite porphyry)

A N 40° E trending llanite dike intersects Texas highway 16 just southwest of the community of Babyhead approximately 9 miles north of Llano. At this locality the dike is 35' wide and intrudes Valley Spring gneiss. This unusual rock has received considerable study and petrological descriptions by Iddings (1904), Washington (1917), Goldich (1941), and Barnes, Dawson, and Parkinson (1947) appear in the literature.

The llanite is a rhyolite porphyry containing phenocrysts of pinkish-red feldspar and blue, opalescent quartz in a bluish-gray to chocolate brown, aphanitic groundmass. Geologic evidence

suggests that this porphyry is the youngest intrusive rock in the Uplift. Two samples of the porphyry were analyzed in order to see if a significant and reproducible lower age was obtainable on the rock. The first sample (14rp-1) was gotten from the east side of the highway where fresh rock is exposed in a road cut. The second sample (14rp-2) was provided by Dr. V. E. Barnes and comes from a small quarry in the porphyry approximately 1/4 mile west of the highway.

The rock consists of approximately 40% phenocrysts and 60% groundmass. Euhedral to subhedral crystals of perthitic microcline averaging 5 mm in diameter and ranging up to 16 mm in maximum dimension comprise over 2/3 of the phenocrysts. The larger feldspar grains commonly contain cores of grayish plagioclase, and small, poikilitic inclusions of biotite are not uncommon. The quartz, which makes up the remainder of the phenocrysts, occurs as rounded to hexagonal crystals averaging 3 mm in diameter. The sky blue color of the quartz has been attributed to reflection and interference phenomena caused by minute crystal inclusions. The groundmass of the porphyry is holocrystalline and composed of microcline, quartz, and albite together with lesser amounts of biotite, fluorite, magnetite, apatite, and zircon. The grain-size of these matrix minerals range from 0.1 mm to submicroscopic. The grains are anhedral in shape and form a granular to micrographic texture.

Microcline separates were obtained from the feldspar phenocrysts in the rock.

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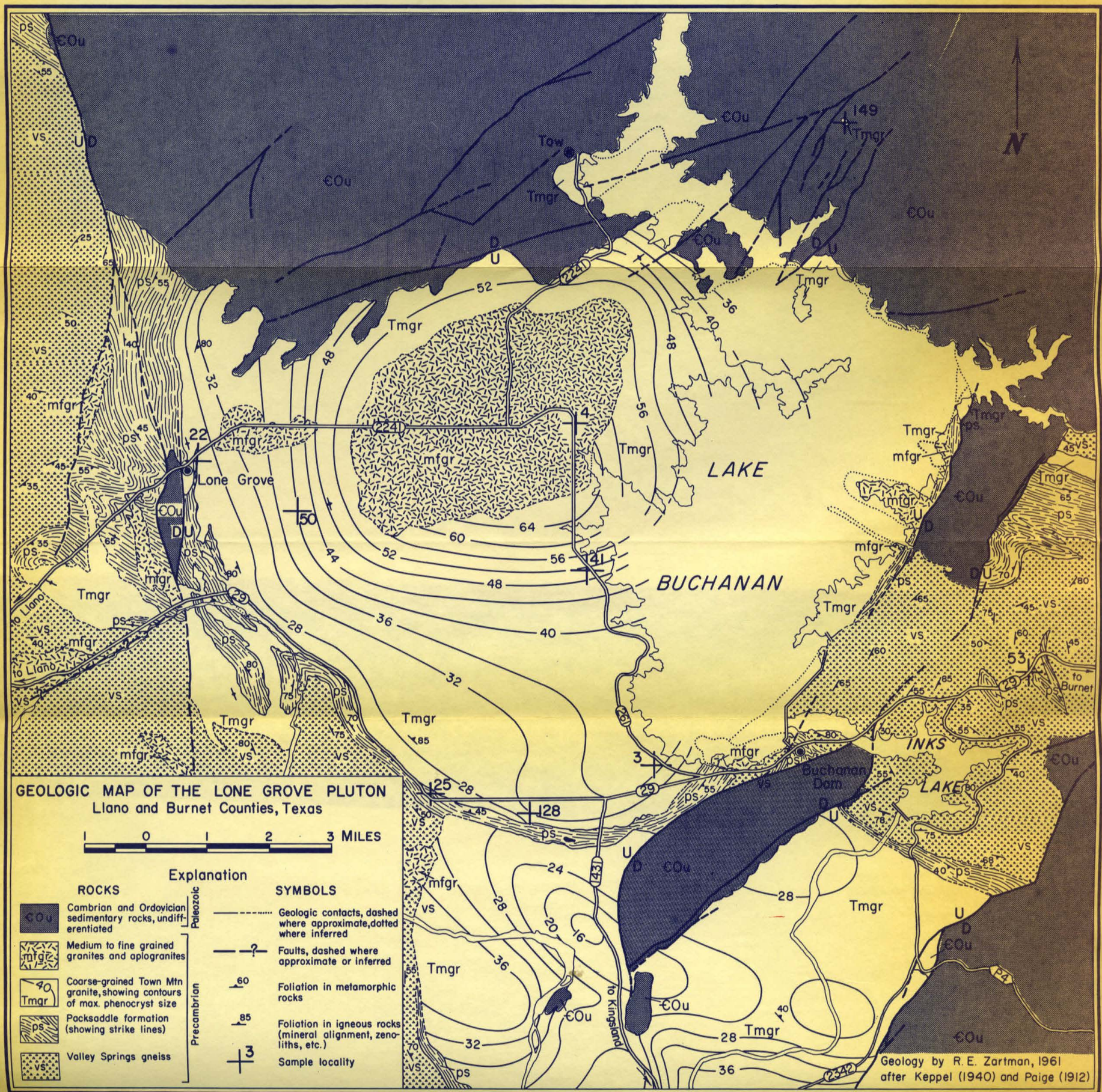
PLATE I


GEOLOGIC MAP OF THE LONE GROVE PLUTON
Llano and Burnet Counties, Texas
1 0 1 2 3 MILES
Explanation
ROCKS
Paleozoic
Precambrian
Cambrian and Ordovician sedimentary rocks, undifferentiated
Medium to fine grained granites and aplogranites
Coarse-grained Town Mtn granite, showing contours of max. phenocryst size
Packsaddle formation (showing strike lines)
Valley Springs gneiss
SYMBOLS
Geologic contacts, dashed where approximate, dotted where inferred
Faults, dashed where approximate or inferred
Foliation in metamorphic rocks
Foliation in igneous rocks (mineral alignment, zenoliths, etc.)
Sample locality
Geology by R. E. Zartman, 1961
after Keppel (1940) and Paige (1912)
LAKE BUCHANAN
INKS LAKE
Lone Grove
Buchanan Dam
to Llano
to Kingsland
to Burnet
Tow
Tmgr
mfgr
ps
vs
€Ou

Rb^{87}-Sr^{87} & K^{40}-Ar^{40} AGES FROM T

AGE, MILLION YEARS			SAMPLE									
			3gr	3ap	3p-1	3p-2	3p-3	3p-4	50gr	41gr	128gr	128W
	Rb^{87}-Sr^{87}	MICROCLINE	1040±30		1040±20		1020±25	1005±25	1005±45	1045±40	1005±25	1000±
		MUSCOVITE										
		BIOTITE	1015±15		830±15	840±15	655±10	955±15	1020±20	975±20	1005±15	955±2
		TOTAL ROCK	1000±40	1010±20								
	K^{40}-Ar^{40}	MICROCLINE	975±10		940±10				945±10			
		PLAGIOCLASE	945±20					855±20				
		MUSCOVITE										
		BIOTITE	1045±10		945±10	980±10	805±10	995±10	1050±10	1025±10	1050±10	1040±
		HORNBLENDE	1050±20					1075±20	980±20	1080±20	1040±20	1030±

M THE LLANO UPLIFT, TEXAS

LOCALITY											
128Wgr	149gr	221gr	222gr	4gr	6gr	20gr	21p	53gn	25 am	14rp-1	14rp-2
1000±25	1000±45	1040±25	1050±25	1015±20	980±40	1030±30		1065±25		935±25	890±20
				1075±20		1035±20	1040±15				
955±20	925±20	730±15	665±15	1025±20	1015±15	1020±15		1025±20			
		960±25									
				915±10				985±10			
				1020±10		1080±10	1075±10				
1040±10	1030±10	1045±10	1035±10	1045±10	1045±10	1075±10		1035±10			
1030±20	1075±20								1035±15		